5. Silicon/silica/SU-8 optical waveguides

- **SOI optical waveguides**
  **Silicon hybrid plasmonic waveguides**
  **Silicon hybrid plasmonic waveguides**
  [18]. **Daoxin Dai** and Sailing He. A silicon-based hybrid plasmonic waveguide with a metal cap for a nano-scal


• SiN optical waveguides

Analysis of the birefringence of a silicon-on-insulator rib waveguide

Daoxin Dai and Sailing He

A detailed analysis of the polarization characteristics (birefringence) of a silicon-on-insulator (SOI) rib waveguide is given. The fundamental TE- and TM-polarized modes of the SOI rib waveguide are calculated by a semivectorial finite-difference method. The rib width and the slab height of the SOI rib waveguide are normalized with respect to the total height of the silicon layer. A general relation between the two normalized parameters for a nonbirefringent SOI rib waveguide is obtained. According to this relation a nonbirefringent SOI rib waveguide can easily be designed. The fabrication tolerance for a nonbirefringent SOI rib waveguide is also analyzed, revealing that the tolerance can be increased by use of a larger total height of the silicon layer. © 2004 Optical Society of America

1. Introduction

It is well known that the polarization state of the light propagating in a standard single-mode fiber (SMF) is random. Consequently, a polarization-independent performance is often desirable for an optical waveguide device used in an optical-fiber system or a network. To reduce the polarization dependence of a photonic lightwave circuit (PLC) device, a few methods, such as using a polarization splitter or inserting a half-wave plate or a waveguide with an undercladding ridge, have been used. However, these methods increase the complexity and cost of the device. A simple and practical method is to use a polarization-independent (i.e., nonbirefringent) planar waveguide device.

Many kinds of optical waveguide structure have been developed, such as buried waveguides, rib waveguides, and strip-loaded waveguides. The most popular materials used for PLCs are Si, SiO$_2$, GaAs, InP, etc. The main cause of birefringence varies among waveguides made of different structures or materials. For example, for a SiO$_2$-on-Si buried waveguide, the stress in the SiO$_2$ film contributes dominantly to the birefringence. For a rib waveguide based on semiconductor materials, the birefringence results mainly from the structural asymmetry. Therefore in this case one can reduce the birefringence by appropriately modifying the geometrical structure of the rib waveguide. When the effective refractive indices of the rib waveguide for the TE and TM modes are equal, a nonbirefringent waveguide is obtained. A spectral-index method and finite-element method have been used to analyze the birefringence of a strip-loaded waveguide and a GaAs rib waveguide, respectively.

Silicon-on-insulator (SOI) wafers have been successfully used, for example, in complementary metal-oxide semiconductor (CMOS) electronic circuits. It has been demonstrated that a SOI rib waveguide has great potential for PLCs, and many PLC devices, such as an arrayed-waveguide grating (AWG) and a star coupler, have been presented. SOI structures also offer the possibility of integrating photonic devices into CMOS electronic circuits. To obtain a polarization-independent a SOI PLC device, one needs to analyze the polarization characteristics of a SOI rib waveguide and design a nonbirefringent waveguide.

In the present paper we use a finite-difference method (FDM) with a perfectly matched layer (PML) boundary treatment to analyze the polarization characteristics of a SOI rib waveguide. To obtain a more general result for the design of a nonbirefringent SOI rib waveguide, we normalize the
slab height and the rib width of a SOI rib waveguide with respect to the total height of the silicon layer and then establish a general relation between these two normalized parameters for a nonbirefringent SOI rib waveguide. Using this general relation, one can easily design a nonbirefringent SOI rib waveguide. The fabrication tolerance for the nonbirefringent SOI rib waveguide is also analyzed.

2. Numerical Method

In the present paper a FDM with a PML boundary treatment is used to calculate the TE and TM modes. In a Cartesian coordinate system, in which the cross section of the waveguide is in the \( x-y \) plane, the full-vectorial wave equation for the electric field can be written in the following form: \(^{12}\)

\[
\begin{pmatrix}
P_{xx} & P_{xy} \\
P_{yx} & P_{yy}
\end{pmatrix}
\begin{pmatrix}
E_x \\
E_y
\end{pmatrix}
= \frac{\partial^2}{\partial x^2}
\begin{pmatrix}
E_x \\
E_y
\end{pmatrix},
\]

where

\[
P_{xx}E_x = \frac{\partial}{\partial x} \left[ \frac{1}{n^2} \frac{\partial (n^2 E_x)}{\partial x} \right] + \frac{\partial^2 E_x}{\partial y^2} + n^2 k_0^2 E_x,
\]

\[
P_{xy}E_y = \frac{\partial}{\partial x} \left[ \frac{1}{n^2} \frac{\partial (n^2 E_y)}{\partial x} \right] - \frac{\partial^2 E_y}{\partial x^2} - \frac{\partial^2 E_y}{\partial y^2},
\]

\[
P_{yx}E_y = \frac{\partial}{\partial y} \left[ \frac{1}{n^2} \frac{\partial (n^2 E_y)}{\partial y} \right] + \frac{\partial}{\partial x} \left[ \frac{\partial E_y}{\partial x} \right] + n^2 k_0^2 E_y,
\]

\[
P_{yy}E_y = \frac{\partial}{\partial y} \left[ \frac{1}{n^2} \frac{\partial (n^2 E_y)}{\partial y} \right] - \frac{\partial}{\partial x} \left[ \frac{\partial E_y}{\partial x} \right],
\]

and where \( n(h, y) \) is the refractive index profile and \( k_0 \) is the wave number in vacuum. The complex coordinates \( \tilde{x} \) and \( \tilde{y} \) are defined by

\[
\tilde{x} = \int_0^1 s_\xi(\zeta')d\zeta' \quad (\zeta = x, y),
\]

where \( s_\xi(\zeta') \) represents a complex stretching variable \(^{12}\) that is usually chosen as

\[
s_\xi(\zeta') = \begin{cases}
1 & \text{in the non-PML region} \\
1 - j \frac{\sigma_{\text{max}}}{\omega \epsilon_0} \frac{\mid \zeta - \zeta_0 \mid^2}{d^2} & \text{in the PML region}
\end{cases},
\]

and where \( \omega \) is the (angular) frequency, \( \epsilon_0 = 8.8542 \times 10^{-12} \text{C}^2/(\text{Nm}^2) \) is the permittivity in vacuum, \( \zeta_0 \) is the PML interface, \( d \) is the thickness of the PML, and \( \sigma_{\text{max}} \) is a constant that can be optimized to minimize the reflection. \(^{12}\) Letting \( E_x = E_x(\tilde{x}, \tilde{y})\exp(-j\beta z) \), \( E_y = E_y(\tilde{x}, \tilde{y})\exp(-j\beta z) \), and substituting them into Eq. (1), one obtains the following semivectorial eigenvalue equations for quasi-TE and quasi-TM modes [with the coupling terms \( P_{xy} \) and \( P_{yx} \) in Eq. (1) neglected]:

\[
P_{xx}E_x = \beta^2 E_x, \quad \text{(4a)}
\]

\[
P_{yy}E_y = \beta^2 E_y. \quad \text{(4b)}
\]

Taking the finite difference (e.g., as used by Stern) \(^{13}\) for Eq. (4a), one obtains the following eigenvalue equation for quasi-TE modes:

\[
a_{mn}E_x(m - 1, n) + b_{mn}E_x(m, n) + c_{mn}E_x(m + 1, n)
+ d_{mn}E_x(m, n - 1) + e_{mn}E_x(m, n + 1)
= \beta^2 E_x(m, n), \quad \text{(5)}
\]

where

\[
a_{mn} = \frac{T_{m-1}}{\Delta \tilde{x}_m \Delta \tilde{y}_m},
\]

\[
b_{mn} = -\frac{1}{\Delta \tilde{x}_m} \left[ \frac{2 - T_{m+1}}{\Delta \tilde{x}_{m+1/2}} + \frac{2 - T_{m-1}}{\Delta \tilde{x}_{m-1/2}} \right]
- \left( \frac{1}{\Delta \tilde{y}_{n+1/2}} + \frac{1}{\Delta \tilde{y}_{n-1/2}} \right)
\frac{1}{1 + n^2 k_0^2},
\]

\[
c_{mn} = \frac{1}{\Delta \tilde{x}_m \Delta \tilde{y}_{n+1/2}},
\]

\[
d_{mn} = \frac{1}{\Delta \tilde{y}_{n+1/2}},
\]

\[
e_{mn} = \frac{1}{\Delta \tilde{y}_n \Delta \tilde{x}_{m+1/2}},
\]

and where

\[
T_{m+1} = 2n_{m+1}^2/(n_{m+1}^2 + n_m^2),
\]

\[
\Delta \tilde{x}_{m+1/2} = \tilde{x}_{m+1} - \tilde{x}_m,
\]

\[
\Delta \tilde{x}_{m-1/2} = \tilde{x}_m - \tilde{x}_{m-1},
\]

\[
\Delta \tilde{x}_m = \tilde{x}_{m+1} - \tilde{x}_{m-1/2}.
\]

In a similar way the corresponding eigenvalue equation for quasi-TM modes can be obtained from Eq. (4b). By solving these eigenvalue equations, one obtains the propagation constants \( \beta_{\text{TE}} \) and \( \beta_{\text{TM}} \) for the fundamental TE and TM modes. The effective refractive indices \( n_{\text{TE}} \) and \( n_{\text{TM}} \) for the TE and TM modes are then given by \( \beta_{\text{TE}}/k_0 \) and \( \beta_{\text{TM}}/k_0 \). The waveguide birefringence \( \Delta n \) is defined as the difference between the effective indices of the fundamental TE and TM modes, i.e.,

\[
\Delta n = n_{\text{TE}} - n_{\text{TM}}. \quad \text{(7)}
\]

3. Results and Discussion

To simplify the analysis for birefringence, the SiO\(_2\) layer is assumed to be thick enough. (The thickness of the SiO\(_2\) layer mainly influences the leakage loss, which is not of interest for the present paper.) The refractive indices for the core and the cladding materials are \( n_1 = 1.0, n_2 = 3.455, \) and \( n_3 = 1.46 \). The wavelength \( \lambda_0 = 1.55 \text{ } \mu\text{m} \). The explicit single mode condition for a SOI rib waveguide with \( r > 0.5 \) is \( t < c + r/(1 - r^2)^{1/2} \), where \( c \) is a constant \((-0.0514 \text{ or } 0.315 \), \( t = W/H, r = h/H, W \) is the rib width, and \( h \) and \( H \) are the slab height and the total height of the Si layer, respectively (see Fig. 1). Here \( t \) and \( r \) are

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the normalized rib width and the normalized slab height, respectively. Because the explicit single-mode condition for a rib waveguide is still under dispute and an explicit condition in the region of $r < 0.5$ has not been established, we use a FDM to determine the single-mode region numerically. The results are shown as crosses in Fig. 1 (the explicit condition with $c = -0.05$ or 0.3 is also indicated in the same figure for a SOI rib waveguide with $r > 0.5$). Such a numerical method is reliable and works for any value of $r$. Our studies show that birefringence of the SOI rib waveguides is not sensitive to wavelengths in the 1.5–1.6 μm window. Therefore we use a wavelength of 1.55 μm in the calculation below.

As a numerical example we first choose the total height of the Si layer as $H = 5$ μm. Figure 2 shows the birefringence of the SOI rib waveguide as the normalized rib width $t$ varies (for several different values of the slab height $h$; i.e., $r = 0.3, 0.4, 0.44, 0.5, 0.6, 0.7$). When the normalized rib width $t$ is very small (approaches zero), the SOI rib waveguide should behave like a slab waveguide of height $h$. Thus the birefringence of the SOI rib waveguide should also be similar to that of the corresponding slab waveguide when $t$ is small. It is well known that the birefringence of a slab waveguide is always positive. Therefore the birefringence of the SOI rib waveguide is also positive when $t$ is very small (this is confirmed in Fig. 2). When $t$ becomes very large, the SOI rib waveguide also behaves like a slab waveguide (with height $H$ for the guiding core layer) and thus has a positive birefringence. Thus for any value of $r$ the birefringence approaches the same positive birefringence value (for a slab waveguide of height $H$) when $t$ becomes very large (this is also confirmed in Fig. 2).

When the normalized slab height $r$ is large, the confinement of the SOI rib waveguide is weak in the horizontal direction, and thus the SOI rib waveguide behaves like a slab waveguide. Because a slab waveguide has a positive birefringence, the birefringence of the SOI rib waveguide is positive for all $t$ when $r$ is larger than a certain critical value $r_0$ ($r_0 = 0.435$ for this numerical example; see the curves for the cases when $r = 0.6, 0.7$ in Fig. 2). A nonbirefringent SOI rib waveguide cannot be obtained when $r > r_0$.

When $r < r_0$, the birefringence $\Delta n$ of the SOI rib waveguide (with a fixed rib height) varies nonmonotonically as the normalized rib width $t$ increases. In Fig. 2 one sees that the birefringence $\Delta n$ has a negative minimal value for such a case. When $t$ increases (starting from a small value), the birefringence $\Delta n$ starts out positive, becomes negative, and then returns to positive values again. This indicates that a nonbirefringent rib waveguide can be designed by appropriately choosing the height and width of the rib. Figure 2 shows that when $r < r_0$ there are two values $t_1$ and $t_2$ ($t_1 < t_2$) for the normalized rib width, which give a nonbirefringent SOI rib waveguide. When $r = r_0$, $t_1$ and $t_2$ are identical. When $r$ decreases (i.e., the slab height $h$ decreases; note that the total height $H$ of the Si layer is fixed here), the difference between $t_1$ and $t_2$ increases.

Figure 3 shows the birefringence of the SOI rib waveguide as the normalized slab height $r$ varies (the rib width $t$ is chosen to be 0.4, 0.6, 0.8, 1.0 and 1.2). From this figure one can see that for each normalized rib width $t$ there is a value of $r$ that gives a nonbirefringent SOI rib waveguide. Figure 3 also shows that the slope of the curve in the vicinity of $\Delta n = 0$ decreases when $t$ increases. This indicates that a larger fabrication tolerance can be obtained for a rib waveguide with a larger normalized rib width $t$.

To facilitate the design of a nonbirefringent SOI rib waveguide, a relation between the normalized rib width $t$ and the normalized slab height $r$ for a nonbirefringent SOI rib waveguide is obtained and shown in Fig. 4. This figure clearly shows that two values ($t_1$ and $t_2$) of the normalized rib width for a
One should choose single-mode requirement greatly limits the ranges of curve, under which the single-mode region lies. The rib waveguide is shown by the double-dotted–dashed mode. In Fig. 4 the single-mode condition for a SOI waveguide devices are often required to be single malized slab height in the range of nonbirefringent waveguide, one should choose a nor-

can be obtained when single-mode SOI rib waveguide without birefringence the single-mode condition. Figure 4 shows that a waveguide as

Nonbirefringent SOI rib waveguide can be obtained when \( r < r_0 \), which is consistent with our previous conclusion drawn from Fig. 2. Figure 4 clearly indicates that \( r_0 = 0.435 \). Therefore when designing a nonbirefringent waveguide, one should choose a nor-

t varies.

Although Fig. 4 is given for the case of \( a_0 = 0 \), which is consistent with our previous conclusion. Figure 4 clearly indi-

cation drawn from Fig. 2. Figure 4 clearly indicates that Fig. 4 is valid for different values of the total

The fabrication tolerance is also very important. For an AWG demultiplexer, the polarization-dependent wavelength (PD\( \lambda \)) is determined by \( \Delta \lambda = \lambda \Delta n / N_c \), where \( \lambda \) is the channel wavelength, \( N_c \) and \( \Delta n \) are the effective refractive index and the birefringence of the arrayed waveguides, respectively. For a SOI rib waveguide \( N_c \approx 3.44 \) and \( \lambda = 1550 \text{ nm} \). Thus \( |\Delta \lambda| < 0.022 \text{ nm} \) when \( |\Delta n| < 5 \times 10^{-5} \). This PD\( \lambda \) is small enough for an AWG demultiplexer with a channel spacing of 0.8 nm (100 GHz). Therefore we choose \( |\Delta n| < 5 \times 10^{-5} \) below to determine the fabrication tolerance zone.

Figure 6(a) shows the fabrication tolerance zone for \( |\Delta n| < 5 \times 10^{-5} \) when \( H = 5 \mu \text{m} \). In this figure the tolerance zone for the normalized rib width \( t \) is the region defined by the dashed curve and the dotted–dashed curve. One can obtain a larger fabrication tolerance by choosing the larger \( (t_2) \) of the two normal-

t varies.

we show below that this figure is also valid for a general case (i.e., for any other values of \( H \)). Figure 5 shows the birefringence of a SOI rib waveguide when \( H = 5 \mu \text{m} \) (dashed curve) and \( 8 \mu \text{m} \) (solid curve). Here one sees that \( t_1 \) and \( t_2 \) for a nonbirefringent SOI rib waveguide (with the same normal-

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On the other hand, waveguides in many optical-waveguide devices are often required to be single mode. In Fig. 4 the single-mode condition for a SOI rib waveguide is shown by the double-dotted–dashed curve, under which the single-mode region lies. The single-mode requirement greatly limits the ranges of \( r \) and \( t \) for a nonbirefringent SOI rib waveguide. One should choose \( t = t_1 \) in the range that satisfies the single-mode condition. Figure 4 shows that a single-mode SOI rib waveguide without birefringence can be obtained when \( r \) is in the range of 0.3–0.435.

Although Fig. 4 is given for the case of \( H = 5 \mu \text{m} \), we show below that this figure is also valid for a general case (i.e., for any other values of \( H \)). Figure 5 shows the birefringence of a SOI rib waveguide when \( H = 5 \mu \text{m} \) (dashed curve) and \( 8 \mu \text{m} \) (solid curve). Here one sees that \( t_1 \) and \( t_2 \) for a nonbirefringent SOI rib waveguide (with the same normal-

The fabrication tolerance is also very important. For an AWG demultiplexer, the polarization-dependent wavelength (PD\( \lambda \)) is determined by \( \Delta \lambda = \lambda \Delta n / N_c \), where \( \lambda \) is the channel wavelength, \( N_c \) and \( \Delta n \) are the effective refractive index and the birefringence of the arrayed waveguides, respectively. For a SOI rib waveguide \( N_c \approx 3.44 \) and \( \lambda = 1550 \text{ nm} \). Thus \( |\Delta \lambda| < 0.022 \text{ nm} \) when \( |\Delta n| < 5 \times 10^{-5} \). This PD\( \lambda \) is small enough for an AWG demultiplexer with a channel spacing of 0.8 nm (100 GHz). Therefore we choose \( |\Delta n| < 5 \times 10^{-5} \) below to determine the fabrication tolerance zone.
the tolerances for $|\Delta n| < 5 \times 10^{-5}$ correspond to $-0.002 < \Delta t < 0.002$ (i.e., $-0.001 \mu m < \Delta W < 0.001 \mu m$) and $-0.073 < \Delta t < 0.2$ (i.e., $-0.365 \mu m < \Delta W < 1.0 \mu m$), respectively. When the single mode is necessary, $-0.073 < \Delta t < 0.1$ (i.e., $-0.365 \mu m < \Delta W < 0.5 \mu m$) for the case of $r = 0.435$. Here $\Delta W$ denotes the deviation of the etching width of the rib, and $H = 5 \mu m$. One sees that the fabrication tolerance is good. Evident from Fig. 5 is that the slope (in the vicinity of $\Delta n = 0$) of the curve for $H = 8 \mu m$ is smaller than that for $H = 5 \mu m$. This indicates that a larger total height of the Si layer gives a larger fabrication tolerance. The tolerance zone of $|\Delta n| < 5 \times 10^{-5}$ for $H = 8 \mu m$ is shown in Fig. 6(b). The range of $r$ for a nonbirefringent SOI rib waveguide is $0.3-0.435$, which is the same as that for $H = 5 \mu m$ (as explained above). Figure 6(b) shows that the tolerance zone is much larger for $H = 5 \mu m$. For example, when $r = 0.435$ ($t_1 = 0.64$) under the single-mode condition, the fabrication tolerance for $|\Delta n| < 5 \times 10^{-5}$ corresponds to $-0.14 < \Delta t < 0.1$ (i.e., $-1.12 \mu m < \Delta W < 0.8 \mu m$). Such a large fabrication tolerance makes the fabrication process much easier. In a standard fabrication process, the accuracy can reach 0.1 $\mu m$. Therefore one can increase the fabrication tolerance by increasing the total height $H$. On the other hand, a rib waveguide with a large cross section (i.e., its spot size matches well with that of a standard SMF) gives a high coupling efficiency to a SMF, and thus the insertion loss of the optical-waveguide device can be reduced.

Bent waveguides are important for some PCs, such as an AWG demultiplexer. In a practical design the bending radius should be large enough for allowable low bending loss. Our numerical results show that the birefringence of a bent SOI rib waveguide with a large bending radius increases slightly as the bending radius decreases. For example, when $H = 5 \mu m$, $r = 0.44$ and $t = 0.64$, the birefringence of a straight waveguide is approximately $1.592 \times 10^{-5}$ (almost nonbirefringent). For a bent waveguide with the same structure, the birefringence is $3.21 \times 10^{-5}$ when the bending radius $R = 5400 \mu m$. One sees that the birefringence of the bent waveguide increases slightly but is still within the $\Delta n$ tolerance of $5.0 \times 10^{-5}$ (determined by the PDG tolerance of 0.022 mm). The pure bending loss of this bent waveguide is approximately 0.0926 dB/90°, indicating that one can achieve a low birefringent bent waveguide with a practical bending radius.

4. Conclusion

In the present paper a semivectorial FDM has been used to analyze the polarization characteristics of a SOI rib waveguide. A general relation between the normalized slab height $r$ and the normalized rib width $t$ for a nonbirefringence has been obtained. When $r > r_0$ ($r_0 = 0.435$ for a typical SOI), one cannot obtain a nonbirefringent SOI rib waveguide. When $r < r_0$, there are two values $t_1$ and $t_2$ ($t_1 < t_2$) of the normalized rib width that give a nonbirefringent SOI rib waveguide. According to the obtained general relation, one can directly choose the two normalized parameters and efficiently obtain a design of a non-birefringent SOI rib waveguide. We have also analyzed the fabrication tolerance for the nonbirefringence. A larger tolerance is obtained when one chooses the larger ($t_2$) of the two normalized rib widths ($t_1$ and $t_2$) for a fixed $r$. However, the smaller one ($t_1$) should be chosen when the rib waveguide must be single mode. To increase the fabrication tolerance, one can increase the total height of the Si layer. Also, the coupling efficiency to a SMF increases owing to a better spot-size match.

This work was supported by the National Natural Science Foundation of China under key project 90101024.
References


Analysis of characteristics of bent rib waveguides

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Received April 24, 2003; revised manuscript received August 11, 2003; accepted September 2, 2003

With a perfectly matched layer boundary treatment, a semivectorial finite-difference method is used to calculate the eigenmodes of a single-mode (SM) or multimode (MM) bent waveguide. A detailed analysis is given for the dependence of the bending losses (including the pure bending loss and the transition loss) on geometrical parameters of the bent rib waveguide such as the rib width, the rib height, and the bending radius. The characteristics of the higher-order modes are analyzed. It is shown that the bending loss of the fundamental mode can be reduced effectively by increasing the width and height of the rib. For an integrated device, undesired effects due to the higher-order modes of a MM bent waveguide can be removed by appropriate choice of the geometrical parameters. An appropriately designed MM bent waveguide is used to reduce effectively the bending loss of the fundamental mode, and a low-loss SM propagation in a MM bent waveguide is realized when the bending losses of the higher-order modes are large enough. © 2004 Optical Society of America

OCIS codes: 130.2790, 230.7370, 230.7380.

1. INTRODUCTION

It is well known that a bent waveguide is an essential element for photonic integrated circuits (PICs). The characteristics of bent waveguides have been given much attention, especially the characteristics of bending losses (including the pure bending loss and the transition loss). Usually, the bending loss increases when the bending radius decreases. Thus one has to increase the bending radius to reduce the bending loss. However, the total size of the PIC will then become large, which is not good for achieving a high integration density.

Rib waveguides are very popular for PICs. When the height of the rib increases, the rib waveguide may become strongly confined, which can reduce the bending loss greatly. The bending loss can also be reduced by increase in the width of the rib. It is well known that a channel waveguide is usually required to be single mode (SM) in many PICs such as arrayed waveguide gratings (AWGs). Therefore the height or width of the rib should be chosen to satisfy the corresponding SM condition. Previous analyses for bent wave guides are mainly for the fundamental mode of a SM bent waveguide.

In the present paper a detailed analysis for a multimode (MM) bent waveguide is given. As we know, the bending loss of a higher-order mode is usually much larger than that of the fundamental mode. By appropriate choice of the geometrical parameters of the bent waveguide, the power of the higher-order modes can attenuate rapidly along the propagation direction, and thus bad effects due to the higher-order modes can be reduced. At the same time, the bending loss of the fundamental mode can be kept low. In this way, only one mode (the fundamental mode) can propagate with a low loss in a MM bent waveguide. When the height or width of the rib increases (and the waveguide becomes MM), the bending loss for the fundamental mode of a bent waveguide is reduced. Thus an appropriately designed MM bent waveguide can be used to reduce effectively the bending loss of the fundamental mode.

2. THEORY

A. Semivectorial Finite-Difference Method

For a bent waveguide, the Dirichlet condition is not appropriate for use as the boundary condition, and a perfectly matched layer boundary treatment is preferred in a FDM. In a complex coordinate system (the cross section of the waveguide is in the xy plane), the full-vector wave equation for the electric field is given by

\[
\begin{pmatrix}
E_x \\
E_y \\
E_z
\end{pmatrix} = \begin{pmatrix}
P_{xx} & P_{xy} \\
P_{yx} & P_{yy}
\end{pmatrix} \begin{pmatrix}
E_x \\
E_y
\end{pmatrix} + \frac{1}{\iiota_x^2} \frac{\partial^2}{\partial x^2} \begin{pmatrix}
E_x \\
E_y
\end{pmatrix},
\]

where

\[
\iiota_x^2 = \iiota_x^2 + \iiota_y^2 + \iiota_z^2.
\]
\[ P_{xx}E_x = \frac{1}{\tilde{t}_x^2} \left( \frac{\partial}{\partial \tilde{x}} \left( \tilde{t}_x \frac{\partial n^2 E_x}{\partial \tilde{x}} \right) \right) + \frac{\partial^2 E_x}{\partial \tilde{y}^2} + n^2 k_0^2 E_x, \]

\[ P_{yy}E_y = \frac{1}{\tilde{t}_x^2} \frac{\partial}{\partial \tilde{y}} \left( \frac{\partial n^2 E_y}{\partial \tilde{y}} \right) - \frac{\partial^2 E_y}{\partial \tilde{x} \partial \tilde{y}}, \]

\[ P_{yx}E_y = \frac{\partial}{\partial \tilde{y}} \left( \frac{1}{\tilde{t}_x^2} \frac{\partial n^2 E_y}{\partial \tilde{x}} \right) + \frac{1}{\tilde{t}_x^2} \frac{\partial}{\partial \tilde{x}} \left( \tilde{t}_x \frac{\partial E_y}{\partial \tilde{x}} \right), \]

\[ + n^2 k_0^2 E_y, \]

\[ P_{yy}E_y = \frac{\partial}{\partial \tilde{y}} \left( \frac{1}{\tilde{t}_x^2} \frac{\partial n^2 E_y}{\partial \tilde{x}} \right) - \frac{1}{\tilde{t}_x^2} \frac{\partial}{\partial \tilde{x}} \left( \tilde{t}_x \frac{\partial E_y}{\partial \tilde{y}} \right), \]

and where \( n \) is the refractive-index profile, \( k_0 \) is the wave number in vacuum, and \( \tilde{t}_x = 1 + \frac{\bar{x}}{R} \) (\( R \) is the bending radius). Let \( E_x = \tilde{E}_x \exp(-j\beta z) \) and \( E_y = \tilde{E}_y \exp(-j\beta z) \). Substituting them into Eq. (1), one obtains the following semivectorial eigenequations for quasi-TE and quasi-TM modes [with the coupling terms \( P_{xy} \) and \( P_{yx} \) in Eq. (1) neglected]:

\[ P_{xx} \tilde{E}_x = \frac{1}{\tilde{t}_x^2} \beta^2 \tilde{E}_x, \tag{2a} \]

\[ P_{yy} \tilde{E}_y = \frac{1}{\tilde{t}_x^2} \beta^2 \tilde{E}_y. \tag{2b} \]

Using a central-grid finite-difference formula for Eq. (2a), one obtains the following eigenequation for quasi-TE modes:

\[ a_{mn} \cdot \tilde{E}_x(m-1, n) + b_{mn} \cdot \tilde{E}_x(m, n) + c_{mn} \]

\[ \cdot \tilde{E}_y(m, n) \quad + d_{mn} \tilde{E}_x(m, n - 1) \]

\[ + e_{mn} \tilde{E}_x(m, n + 1) = \beta^2 \cdot \tilde{E}_x(m, n), \tag{3} \]

where

\[ a_{mn} = \frac{n_{m-1}^2(1 + \bar{x}_{m-1}/R)}{2\Delta x_{m-1} \Delta x_{m-1/2}} \times \left( \frac{1 + \bar{x}_{m-1}/R}{n_{m-1}^2} + \frac{1 + \bar{x}_m/R}{n_m^2} \right), \]

\[ b_{mn} = \frac{(1 + \bar{x}_m/R)n_m^2}{2\Delta x_m} \times \left( \frac{1 + \bar{x}_{m+1}/R}{n_{m+1}^2} + \frac{1 + \bar{x}_m/R}{n_m^2} \right) \frac{1}{\Delta x_{m+1/2}} \]

\[ + \frac{(1 + \bar{x}_{m-1}/R)^2}{n_{m-1}^2} \frac{1}{\Delta x_{m-1/2}} \]

\[ - \frac{(1 + \bar{x}_m/R)^2}{\Delta y_{m+1/2} \Delta y_{m-1/2}}, \]

\[ c_{mn} = \frac{n_{m+1}^2(1 + \bar{x}_{m+1}/R)}{2\Delta x_{m+1} \Delta x_{m+1/2}} \times \left( \frac{1 + \bar{x}_{m+1}/R}{n_{m+1}^2} + \frac{1 + \bar{x}_m/R}{n_m^2} \right), \]

\[ d_{mn} = \frac{(1 + \bar{x}_m/R)^2}{\Delta y_{m+1/2} \Delta y_{m+1/2}}, \]

\[ e_{mn} = \frac{(1 + \bar{x}_m/R)^2}{\Delta y_{m+1} \Delta y_{m+1/2}}. \]

and where \( \Delta x_{m+1/2} = \bar{x}_{m+1} - \bar{x}_m, \quad \Delta x_{m-1/2} = \bar{x}_m - \bar{x}_{m-1}, \) and \( \Delta y_m = \bar{y}_{m+1} - \bar{y}_{m-1} \). In a similar way, the corresponding eigenequation for quasi-TM modes can be obtained from Eq. (2b). By solving these eigenequations, one can obtain the eigenvectors (i.e., the modal field distributions) and the corresponding eigenvalues (i.e., the propagation constants for the eigenmodes). The real and imaginary parts of the propagation constant represent the phase variation and the pure bending loss, respectively.

### B. Bending Losses

For a \( \pi/2 \) bent waveguide with a bending radius \( R \), the pure bending loss is given by

\[ L_n = 20 \log_{10} \exp(\pi/2 \times \beta/R) \] [decibels (dB)/90°]. \tag{4} \]

For a bent waveguide, the peak of the modal field distribution shifts outward and deviates from the center of the waveguide in the lateral direction. The deviation increases as the bending radius decreases. When two bent waveguides with different bending radii are connected to each other, a transition loss occurs owing to the mismatch of the modal fields. The transition loss can be calculated with the overlapped integral method. The transition loss at the junction between a straight waveguide and a bent waveguide can be calculated by
where \( E_0(x, y) \) and \( E_0^*(x, y) \) are the modal fields for the straight waveguide and the bent waveguide, respectively.

### 3. RESULTS AND DISCUSSIONS

To confirm that the FDM code used in this paper is correct, we first calculate the pure bending loss for an example (shown in the inset of Fig. 1) considered earlier in the literature and give the comparison results in Fig. 1. The solid curve, the dotted--dashed curve, and the dashed curve show the pure bending loss calculated by the present FDM, the finite-element method (FEM), and the method of lines (MOL), respectively. From Fig. 1, one can see that the results obtained with our FDM code agree well with earlier results in the literature.

In the rest of the paper, we choose a SOI (silicon-on-insulator) rib waveguide to analyze. The SM condition for a SOI rib waveguide is given by

\[
L_p = -10 \log \left[ \left( \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} E_0(x, y) E_0^*(x, y) \, dx \, dy \right) \right]
\]

and

\[
L_p = -10 \log \left[ \left( \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} E_0(x, y) E_0^*(x, y) \, dx \, dy \right) \right] + 10 \log \left( \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} E_0(x, y) E_0^*(x, y) \, dx \, dy \right)
\]

(dB), (5)

For example, when \( R = 10,000 \mu m \) the pure bending loss is reduced by 10.893 dB as the rib width increases from 4 to 5 \( \mu m \) [see Fig. 3(a)]. However, the reduction in the pure bending loss is only 0.318 dB when the rib width increases from 6 to 8 \( \mu m \).

From Fig. 3(b) one sees that the transition loss decreases to a minimal value and then starts to increase as the rib width increases for a fixed bending radius. This is different from the monotonous characteristic of the pure bending loss shown in Fig. 3(a). The transition loss as the rib width increases for different bending radii is shown in Fig. 4, from which one can see that there exists an optimal value of the rib width for a minimal transition loss. The optimal width is not sensitive to the bending

![Fig. 1. Comparison of the pure bending loss calculated with the present FDM code, FEM, and MOL for an example (shown in the inset) considered in Ref. 5.](image)

![Fig. 2. SM region and the MM region for a SOI rib waveguide.](image)
Thus we choose a fixed bending radius to show how the transition loss varies as the rib width increases for different rib heights in Fig. 5. Here the bending radii are chosen in such a way that the pure bending loss is lower than 0.1 dB/90°. From Fig. 3(a) one sees that the corresponding bending radii are 11,800, 4550, and 1800 μm for the cases of \( h_r = 2, 2.5, \) and 3 μm, respectively.

From Fig. 5 one can see that the optimal value of the rib width increases when the rib height decreases. This can be explained by analysis of the field distribution of the fundamental mode. Figures 6(a)–6(c) show the fundamental modal fields for the cases of \( w_r = 4, 6, \) and 8 μm, respectively, when \( R = 10,000 \) μm and \( h_r = 2 \) μm. From these figures one can see that when the rib width increases the power leaking outward decreases, which results in a reduction of the transition loss. However, at the same time the peak deviation of the field distribution from the central axis of the waveguide increases (see Fig. 5), which increases the transition loss. Figure 6 shows that the peak deviations are approximately 0.25, 0.4, and 0.9 μm when \( w_r = 4, 6, \) and 8 μm, respectively. Both factors affect the transition loss and result in a nonmonotonic variation of the transition loss as shown in Fig. 5. The above transition loss is calculated when the central axis of the straight waveguide coincides with that of the bent waveguide. For a weakly confined waveguide, one can reduce further the transition loss by introducing a lateral offset between the central axes of the straight waveguide and the bent waveguide. However, for a SOI rib waveguide, such a lateral offset will cause a facet reflection, since the refractive-index difference between Si and air is very large.

Compared with the increase of the rib width, the increase of the rib height can reduce the bending loss more effectively. According to the SM condition given by inequality (6), higher-order modes will appear when the rib width or height increases. The higher-order modes will introduce some undesired effects for an integrated waveguide device, for example, the cross talk between adjacent channels in an AWG.

Here we analyze the higher-order modes for the case of \( h_r = 3 \) μm. Figures 7(a)–7(f) show the pure bending
loss and the transition loss for the fundamental mode ($E_{11}^x$) and the higher-order modes ($E_{21}^x$ and $E_{12}^x$) as the bending radius increases. Here the transition loss for a higher-order mode refers to the coupling loss from the fundamental mode of the straight waveguide to the higher-order mode of the bent waveguide.

From Figs. 7(a) and 7(b) one can see that the characteristics of the fundamental mode (here $h_r = 3.0 \mu m$) are similar to those shown in Figs. 3(a) and 3(b) (where $h_r = 2.0 \mu m$). However, the minimal bending radius (with an allowable pure bending loss of 0.1 dB/90°) is much smaller than that of the previous case when $h_r = 2.0 \mu m$.

Figure 7(c) indicates that the pure bending loss of the $E_{21}^x$ mode decreases as the bending radius increases, which is similar to the case of the fundamental mode. When the rib width increases, the pure bending loss for the $E_{21}^x$ mode decreases (this is because the $E_{21}^x$ mode is far from the cutoff). When $w_r = 4.0 \mu m$, the pure bending loss for the $E_{21}^x$ mode increases as the bending radius increases, which may look unreasonable. This is because the pure bending loss is given per 90° (instead of per centimeter) in Fig. 7(c). In fact, our calculation results have shown that the pure bending loss per centimeter decreases (as expected) when the bending radius increases.

The transition loss for the $E_{21}^x$ mode is shown in Fig. 7(d), from which one can see that the transition loss decreases to a minimal value and then increases as the bending radius increases. This can be explained by analysis of the field distribution of the $E_{21}^x$ mode. The modal field distorts significantly when the bending radius is very small. When the bending radius increases, the distortion is reduced, and the coupling efficiency between the fundamental mode of the straight waveguide and the $E_{21}^x$ mode of the bent waveguide increases (i.e., the transition loss is reduced). However, when the bending radius increases further, the modal field of the bent waveguide becomes similar to that of a straight waveguide, and thus the $E_{21}^x$ modal field approaches an odd symmetry. Since the fundamental mode of a straight waveguide has an even symmetry, the coupling efficiency (between the fundamental mode of the straight waveguide and the $E_{21}^x$ mode of the bent waveguide) decreases when the bending radius increases further. When the bending radius approaches infinity, the transition loss for the $E_{21}^x$ mode also approaches infinity.

From Fig. 7(d) one can also see that the transition loss for the $E_{21}^x$ mode decreases when the rib width increases. For a bent waveguide, the peak of the modal field distribution (for both odd and even modes) deviates from the central axis of the waveguide. When the rib width increases, the symmetries of the modes are more distorted, and thus the coupling efficiency (between the fundamental mode of a straight waveguide and the $E_{21}^x$ mode of a bent waveguide) increases (i.e., the transition loss decreases).

The pure bending loss and the transition loss for the $E_{12}^x$ mode are shown in Figs. 7(e) and 7(f), respectively. From Fig. 7(f) one sees that the transition loss for the $E_{12}^x$ mode increases as the bending radius increases (this is similar to the case of $E_{21}^x$ shown in Fig. 7(d)). The pure bending loss for the $E_{12}^x$ mode is shown in Fig. 7(e), which is quite different from Fig. 7(c) for the $E_{21}^x$ mode. From Fig. 7(e) one can see that the characteristics of the pure bending loss for the $E_{12}^x$ mode differ very much for differ-
ent rib widths. For example, when $w_r = 4.0 \, \mu m$ the pure bending loss for the $E_{12}^{x}$ mode increases to a maximal value and then decreases as the bending radius increases. Like Fig. 7(c), the nonmonotonic behavior of Fig. 7(e) is due to the fact that the pure bending loss is given per 90° (instead of per centimeter). Our calculation has shown...
that the pure bending loss per centimeter decreases monotonously (as expected) when the bending radius increases. For the case of \( w_x = 5.0 \mu m \), the pure bending loss for the \( E_{11}^z \) mode decreases as usual when the bending radius increases. When \( w_x = 5.5 \) and 6.0 \( \mu m \), the curves of the pure bending loss are nonmonotonous in Fig. 7(e) for the \( E_{11}^z \) mode. The pure bending loss decreases to a minimal value, then increases to a maximal value, and then again decreases when the bending radius increases. This strange behavior can still be explained from analyzing the field distributions of the \( E_{11}^z \) modes shown by Figs. 8(a)–8(f) for bent waveguides with different radii \( (R = 10,000, 5000, 2000, 1000, 800, \) and 500 \( \mu m \), respectively).

From these figures one can see that there are two peaks (referred to as the top peak and the bottom peak) in the vertical direction for the \( E_{12}^z \) mode. When the bending radius decreases from a very big value (close to infinity), both peaks shift outward, and the power leaking outward increases [see Figs. 8(a) and 8(b)]. The outward shift of the top peak is less than that of the bottom peak, since the top peak is more confined (by the rib). In this case the pure bending loss mainly results from the leakage loss of the bottom peak. When the bending radius decreases further, the top peak shifts outward further. However, the outward shift is prevented by the confinement of the rib. The outward shift of the top peak becomes a downward shift. The top peak is compressed in the lateral direction while being extended in the vertical direction [see Fig. 8(c)]. At the same time, the bottom peak is squeezed by the top peak, and thus the outward shift of the bottom peak is prevented by the top peak, which reduces the power leaking outward from the bottom peak. Thus the pure bending loss [dominated by the leakage from the bottom peak in this case; see Fig. 8(d)] of the bent waveguide is reduced. When the bending radius decreases further, the top peak shifts downward so much that it lies below the rib, and thus the power leaking outward from the top peak increases [see Figs. 8(e) and 8(f)]. Therefore the pure bending loss (dominated by the leakage from the top peak in this case) increases when the bending radius decreases further.

To remove the bad effects caused by the higher-order modes, one should ensure that the pure bending loss and the transition loss of the higher-order modes are large enough. A large transition loss means the power coupled from the fundamental mode to a higher-order mode is small. A large pure bending loss means the coupled power will attenuate rapidly along the propagation direction. Thus one should choose a small bending radius to make the pure bending loss of the higher-order modes large enough. On the other hand, Figs. 7(d) and 7(f) show that the bending radius should be chosen large enough to obtain a large transition loss. In addition, the low bending loss of the fundamental mode \( E_{11}^z \) also requires the bending radius to be large enough (typically, the pure bending loss and the transition loss are required be lower than 0.1 dB). Therefore geometrical parameters such as the rib height, the rib width, and the bending radius should be chosen appropriately. By optimizing the geometrical parameters of the bent waveguide, we can let only one mode (the fundamental mode) propagate with a low loss in a MM bent waveguide.

As a numerical example, we require the transition loss and the total bending loss for higher-order modes to be larger than 20 and 60 dB, respectively. We choose \( h_y = 3.0 \mu m \), and the other geometrical parameters can be determined from Figs. 7(a)–7(f) as follows:

1. The case of \( w_x = 6 \mu m \). According to the loss requirement for modes \( E_{11}^z \), \( E_{12}^z \), and \( E_{21}^z \), the bending radius \( R \) should be larger than 4000, 2000, and 8000 \( \mu m \), respectively. Thus we should choose \( R \approx 8000 \mu m \).
2. The case of \( w_x = 5 \mu m \). To satisfy the loss requirement for the modes of \( E_{11}^z \), \( E_{12}^z \), and \( E_{21}^z \), we should let \( R \) be larger than 2500, 3000, and 2250 \( \mu m \), respectively. Thus we choose \( R \geq 3000 \mu m \).
3. The case of \( w_x = 4 \mu m \). To satisfy the loss requirement for the fundamental mode (\( E_{11}^z \)), \( R \) should be larger than 2250 \( \mu m \), for which the bending losses for \( E_{12}^z \) and \( E_{21}^z \) are large enough [see Figs. 7(c)–7(f)]. Thus we choose \( R > 2250 \mu m \).
4. The case of \( w_x = 3.5 \mu m \). To satisfy the low-loss requirement for the fundamental mode, \( R \) has to be larger than 2750 \( \mu m \). The corresponding bending loss for \( E_{12}^z \) is large enough [see Figs. 7(e) and 7(f)]. Thus we choose \( R > 2750 \mu m \) (the \( E_{21}^z \) mode does not exist in this case).

Therefore, for the same loss requirement in the above four cases, the bending radius is the smallest (2250 \( \mu m \)) when \( w_x = 4 \mu m \). From Fig. 5 one can also see that the optimal value for the rib width is approximately 4 \( \mu m \) when \( h_y = 3.0 \mu m \).

B. Design Procedure for a Bent Waveguide

Here we illustrate the design procedure with a specific example. Figure 9 shows the SOI rib waveguide structure to be designed, which is a part of an arrayed waveguide in an AWG demultiplexer. The arc is 60°. The optimal design for such a structure can be described as follows.

1. Determine the height and the width of the rib for the straight rib waveguide parts according to the SM condition and other requirements such as the coupling efficiency between the rib waveguide and a standard SM fiber. In this example, we have \( h_y = 3 \mu m \) and \( w_x = 3 \mu m \) for the straight rib waveguide parts.
2. To avoid any additional etching process, we ensure that the bent waveguide has the same rib height as the straight rib waveguide [determined in step (1)]. We then determine the optimal values for the rib width of the bent waveguide and the bending radius in the way given in the numerical example at the end of Subsection 3.A. The bending radius is determined according to the allowable loss for the fundamental mode and the minimal loss for the higher-order modes. In this numerical example, the optimal rib width of the MM bent waveguide is 4 \( \mu m \), and the bending radius is determined to be 2250 \( \mu m \).
3. Connect the two straight waveguides with the bent waveguide by use of two adiabatic tapered waveguides. The length of the taper section is 1200 \( \mu m \).
A three-dimensional finite-difference beam-propagation method\textsuperscript{9,10} (with a perfectly matched layer boundary treatment) is used to simulate the light propagation in the structure. If the bent waveguide has the same rib width as the straight rib waveguide (i.e., $3 \mu m$), the total propagation loss is approximately 1.41 dB. When we increase the rib width of the bent waveguide to $4 \mu m$ (the optimally designed rib width), the total propagation loss
can be reduced to approximately 0.34 dB, which includes the loss in the two tapered sections (approximately 0.05 dB for each tapered section).

One can see that the bending loss of the fundamental mode in this structure is reduced significantly and the bad effects due to the higher-order modes are also reduced. Such a structure can be used to make the PIC more compact and thus improve the integration density.

4. CONCLUSION
The modal characteristics in a bent rib waveguide have been analyzed. The pure bending loss and the transition loss have been calculated and discussed. It has been shown that the bending radius can be reduced effectively by increase in the width and height of the rib. The undesired effects due to higher-order modes can be reduced when the bending losses of the higher-order modes are large enough. Thus a low-loss SM propagation in a MM bent waveguide can be realized. An arrayed waveguide in an AWG demultiplexer has been designed as a numerical example to illustrate the present design procedure. The numerical results given by the three-dimensional finite-difference beam-propagation method have shown that the bending loss for the fundamental mode of an appropriately designed MM bent waveguide can be much smaller than the bending loss for the fundamental mode of a SM bent waveguide with the same bending radius.

ACKNOWLEDGMENT
This research is supported by the Government of Zhejiang Province, China, under a major research grant (No.001101027).

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REFERENCES
Characteristic analysis of nanosilicon rectangular waveguides for planar light-wave circuits of high integration

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When a full-vectorial finite-difference method is used, rectangular Si waveguides can be characterized for planar light-wave circuits of high integration. The single-mode condition for a rectangular Si waveguide is obtained first. The birefringence, which can be adjusted by modifying the thickness of the cladding layer, is also studied. For a nano-Si rectangular waveguide the pure bending loss is very small even for an ultrasmall bending radius (e.g., a few micrometers), and the transition loss becomes dominant. The width and height are optimized to minimize the bending radius for the requirement that the bending loss is smaller than 0.1 dB. Finally the coupling between two parallel straight waveguides is analyzed, and it is shown that there is an optimal width for the maximal coupling length. © 2006 Optical Society of America

OCIS codes: 130.3120, 060.1810.

1. Introduction

Optical devices based on planar light-wave circuits (PLCs) are attractive because of their excellent performance and compact size. Many materials and structures for optical waveguides have been developed, among which the SiO$_2$ buried rectangular waveguide is the most popular. However, for a SiO$_2$ buried waveguide (even with a superhigh refractive index contrast, $\Delta = 2.5\%$), the bending radius has to be at least several millimeters for an acceptable bending loss. Furthermore, the separation between two parallel SiO$_2$ buried waveguides should be ~20 $\mu$m to avoid coupling between them. This limits its application for achieving a higher integration density.

A waveguide based on a silicon on insulator (SOI) is a good choice for realizing a higher integration density because of the great difference in the refractive indices between the core (Si) and the cladding or insulator (air or SiO$_2$). However, SOI rib waveguides that have been used popularly for PLC devices still have a large cross section (several micrometers). To satisfy the single-mode condition, the SOI rib waveguide is etched shallowly, which gives a weak confinement. In this case a high integration density is impossible. Recently the great difference between the refractive indices of Si and SiO$_2$ (or air) has attracted more attention, and the size of the Si waveguide is reduced to several hundred nanometers. This kind of Si waveguide is usually called a nano-Si rectangular waveguide. The scattering loss (per unit length) for a nano-Si rectangular waveguide because of the roughness of the sidewall is much larger than that for a conventional waveguide of micrometer dimensions. On the other hand, the total size of the PLC devices based on nanowaveguides are reduced significantly, which compensates for the large scattering loss per unit length. Consequently the total loss in a PLC device based on nanowaveguides can be sufficiently low for practical use. Some experimental results on the measurement and reduction of the scattering loss in the nanoscale Si rectangular (instead of rib) waveguides have been reported. In particular, some techniques have been developed to reduce the scattering loss by smoothing the sidewall. Therefore developing ultrasmall PLC devices based on nano-Si rectangular waveguides is becoming more and more attractive. In the design of PLC devices, theoretical analysis is important. Some theoretical results for SiO$_2$ nanowires (of circular cross section) have been reported. However, little has been reported so far on the characteristic analysis of nano-Si rectangular waveguides. In this paper we use a full-vectorial finite-difference method (FDM) to calculate the eigen-
modes of a nano-Si rectangular waveguide and analyze its characteristics in detail, including the single-mode condition, the birefringence, the bending loss, and the coupling between two parallel waveguides. One can obtain, based on these detailed analyses, the optimal size of a nano-Si rectangular waveguide for a highly integrated PLC.

2. Analysis and Discussion

A. Single-Mode Condition

An optical waveguide is usually required to be single mode to avoid the influence from higher-order modes. Therefore it is important to determine the single-mode condition before the PLC is designed. We consider a specific wavelength, $\lambda = 1550$ nm, for the analysis given below. The refractive indices of the core (Si) and the cladding (SiO$_2$) are $n_{co} = 3.455$ and $n_{cl} = 1.46$, respectively. Figure 1 shows the cross section of the considered nano-Si rectangular waveguide, where the thickness of the cladding is $h_{cl}$ and the buffer layer is sufficiently thick (except for Fig. 4). A full-vectorial FDM is used to calculate the effective indices of the TE- and the TM-polarized modes for the nano-Si rectangular waveguide. To obtain the single-mode condition, we scan the width and height and check whether the higher-order modes are supported in the rectangular Si waveguide considered. For a fixed height we reduce the width at a step of 5 nm until all the higher-order modes disappear. The calculated results are shown in Fig. 2, where the horizontal and the vertical axes are the width $w$ and height $h$, respectively, of the core. The curve indicates the critical boundary under which the single-mode region lies. One sees that the size of the core for a single-mode Si waveguide is of the order of several hundred nanometers, which is smaller than one tenth the size of a conventional waveguide (e.g., a SiO$_2$ buried waveguide or a SOI rib waveguide). This is due to the great contrast in the refractive indices between the core (silicon) and the cladding (SiO$_2$ or air). Therefore it is possible to realize a PLC with a very high integration density.

B. Birefringence

Polarization-independent performance is often desirable for PLC devices. A simple and practical method for achieving this is to use a polarization-independent (i.e., nonbirefringent) waveguide. The birefringence $B$ (defined as the difference in the effective refractive indices between the TE and the TM modes, i.e., $B = n_{TE} - n_{TM}$) of an optical waveguide mainly results from the geometrical asymmetry or the material anisotropy due to, e.g., the thermal stress in a silica buried waveguide. In a nano-Si rectangular waveguide, the birefringence due to thermal stress (produced in an annealing process) is usually not significant. This is because the Si core is very small, the SiO$_2$ insulator and cladding layers are thin (no more than 2 $\mu$m), and the annealing process is not necessary. Therefore in this paper we consider only the birefringence due to the geometrical asymmetry of a nano-Si rectangular waveguide.

First we consider the case in which both the SiO$_2$ cladding and the buffer layers are infinitely thick (i.e., $h_{cl} = \infty$). Figure 3(a) shows the effective refractive index as the core width varies for different heights, and Fig. 3(b) shows birefringence $B$. For a fixed height the effective refractive index increases as the core width increases and approaches the value of the effective refractive index for a slab waveguide with the same height. From Fig. 3(b) one sees that the birefringence is negative when the width is smaller than the height. The birefringence becomes positive when the width is greater than the height. When the width and height are the same, the effective refractive indices for the TE and the TM modes are the same (as expected), i.e., $B = 0$ [see Fig. 3(b)]. When a nonbirefringent nano-Si rectangular waveguide is desirable, one should choose a height and width that are the same. From Fig. 3(b) one sees that the nonbirefringent structure is sensitive to the width and height of the core. The slope of the curve at the nonbirefringent point is larger when the size of the core is smaller. This indicates that a nonbirefringent design is more sensitive to the size variation of the core for a nano-Si rectangular waveguide with a smaller core, which results in a more critical control in the fabri-
cation process. When the width is larger than 775 nm, the birefringence becomes less sensitive to the size variation of the core.

Next we consider the birefringence $B(h_{cl})$ of a nano-Si rectangular waveguide as the thickness $h_{cl}$ of the SiO$_2$ cladding layer varies. Figure 4 shows the difference in $B(h_{cl}) - B(h_{cl} = \infty)$. Here the thickness of the buffer layer is sufficiently thick. Figure 4 shows that the influence of the cladding thickness on the birefringence is smaller when the core height $h$ is larger. One sees that the birefringence becomes less sensitive to the thickness $h_{cl}$ when $h_{cl} > 400$ nm. The thickness influences the birefringence greatly when $h_{cl} < 400$ nm. Therefore one can choose the thickness $h_{cl}$ to be large enough to increase the fabrication tolerance. On the other hand, one can adjust the birefringence of a nano-Si rectangular waveguide by controlling the thickness accurately with a good fabrication technology.

C. Bending Loss

The minimal bending radius (fulfilling the requirement of the bending loss, $L < 0.1$ dB) is one of the most important factors for the integration density. Theoretically speaking, the bending loss should include the pure bending loss $L_p$ and the transition loss $L_t$. For a bending waveguide the peak of the modal field shifts to the outside, which introduces a mismatch in the modal profile at the junction between a straight waveguide and a bent waveguide and consequently results in the transition loss. Furthermore, when the modal field shifts to the outside, it overlaps the sidewall roughness more and thus introduces some additional scattering loss (compared with a straight waveguide). Therefore only a small shift in the field peak is allowed in order to make the transition loss and the additional scattering loss small. When the shift in the field peak is small enough, the scattering loss (per unit length) of the bending section should be almost the same as that of a straight section ($\sim 2.4$ dB/cm). Since the bending section is very short (no more than 10 $\mu$m), the total scattering loss of the bending section should be as small as 0.0024 dB. Therefore we focus on the analysis of the pure bending loss and transition loss. Here we consider the pure bending loss for a 90° bent waveguide. The calculated pure bending loss and transition loss (for the TE and the TM modes) are shown in Figs. 5(a) and 5(b), respectively.

Here we choose the height, $h = 400$ nm, and width, $w = 250, 300, 400, 500$ nm. From Fig. 5(a) one sees that the pure bending losses (for a 90° bending waveguide) of the TE- and the TM-polarized modes are quite different, especially when the width is small. For example, when $w = 250$ nm, the pure bending loss for the TE mode is much larger than that of the TM mode, $L_p(TE) \approx 1.097$ and $L_p(TM) \approx 0.0195$ dB, respectively. The pure bending loss for the TE mode decreases rapidly and becomes almost the same as that for the TM mode when $w = h$. When the width is greater than the height, the pure bending loss for the TE mode is

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**Fig. 3.** (Color online) (a) Effective refractive indices of the TE- and the TM-polarized fundamental mode; (b) birefringence with $h_{cl} = \infty$.

**Fig. 4.** (Color online) Birefringence as the thickness $h_{cl}$ of the cladding increases.
smaller than that for the TM mode. If one considers only the pure bending loss, the bending radius can be as small as 1.5 μm when \( w > 300 \) nm (in the case of \( h = 400 \) nm). A lower pure bending loss can be achieved when a larger width is chosen for a fixed bending radius. However, one should consider the transition loss, which is dominant when the width is large (shown in Fig. 5(b)]. In this case a larger width is not a good choice (even the pure bending loss is lower). Figure 5(b) shows the transition losses for the TE and the TM modes. From Fig. 5(b) one sees that the transition loss is not very sensitive to the width, which is different from the pure bending loss [shown in Fig. 5(a)]. For the TE mode, when the width increases, the transition loss decreases first and then increases, which is different from the monotonous decrease of the pure bending loss shown in Fig. 5(a).

For the design of a bent waveguide one should consider the total loss (the sum of the pure bending loss and the transition loss). Here we consider a 90° bent waveguide connected with two straight waveguides at the ends, and the total loss is

\[ L = L_p + 2L_t. \]

Figure 6(a) shows the total bending loss for the TE and the TM modes. One sees that the difference in the total loss between the TE and the TM modes is the smallest when \( w = 300 \) nm. Since the total bending loss should be smaller than 0.1 dB for both the TE and the TM modes and the polarization-dependent loss (PDL) should be sufficiently small, we should choose an appropriate width so that the bending radius is minimal for high integration. Figure 6(b) shows the PDL as the bending radius varies for different widths. One sees that the PDL first decreases and then increases when the width increases. One can find an optimal width as follows. First, for a fixed width find the minimal bending radius. (The total loss should be no more than 0.1 dB for both polarizations; PDL is then small enough.) Then plot a curve for this minimal bending radius as the width varies, from which the optimal width with the minimal bending radius can be determined. Here we found that the optimal width is \( w = 300 \) nm. In this case the minimal bending radius is \( \sim 2.7 \) μm (corresponding to a total bending loss of 0.1 dB). From Fig. 6(b) one sees that for this optimal width (w = 300 nm) the PDL is very small in a large range of the bending radius. In this optimization one should also consider the single-mode condition. Actually the optimal bending waveguide obtained (300 nm \( \times \) 400 nm) is not strictly single
mode. (Some higher-order modes are close to the cutoff.) The loss in the higher-order modes is much greater than that in the fundamental mode (i.e., the higher-order modes attenuate quickly along the propagation direction); thus the optimal design is effectively single mode.

D. Coupling Length

The coupling between two parallel straight waveguides (Fig. 7) is also important in the design of PLC devices. The coupling length determines how close two adjacent waveguides can be placed, which is also one of the most important factors in determining the integration density. (The other is the minimal bending radius; see Subsection 2.C.)

Figure 8 shows the coupling length (for the TE mode) as the core width $w$ varies when the separation distance $D$ between the two parallel waveguides is chosen to be $D = 0.6, 1.0, 1.2,$ and $1.6 \, \mu m$. We consider the cases in which the core height $h = 300, 400,$ and $500 \, \text{nm}$. One sees that the coupling length is larger for a larger core height $h$ (for the same width $w$ and separation $D$). This is because the confinement of the modal field in a waveguide of larger height (e.g., $h = 500 \, \text{nm}$) is stronger. Since the high integration density is desirable only in the lateral direction (instead of the vertical direction) for a PLC, it is an effective way to increase the coupling length (corresponding to the improvement in the integration density) by increasing the core height. Furthermore a nano-Si rectangular waveguide with a larger core height allows a smaller bending radius and is easier for coupling a fiber. Thus, in the design of a PLC based on a nano-Si rectangular waveguide, choosing a large core height is preferred. However, a nano-Si rectangular waveguide should be single mode, and polarization sensitivity is another issue that should be considered.

From Fig. 8 one also sees that the coupling length increases first and then decreases when the core width increases for a fixed separation distance $D$ (which can indicate the integration density more appropriately than gap $d$). Thus there exists an optimal width, $w = w_0$, for a maximal coupling length. The existence of an optimal width (for the maximal coupling length) can be explained as follows. When the width increases, the confinement of the nano-Si rectangular waveguide becomes stronger, and consequently the evanescent coupling between the two parallel waveguides tends to decrease. On the other hand, the gap $d = D - w$ between the two parallel waveguides becomes narrower (since the separation $D$ is fixed), and consequently the influence between the two parallel waveguides increases. To improve the integration density, one should choose the optimal width, $w = w_0$, so that the decoupled separation distance between the two adjacent waveguides can be minimal. Since the slope of the curve at $a = a_0$ is zero, the fabrication tolerance to the optimal width is also good. Figure 9 shows the optimal width $w_0$ as the separation $D$ varies for the cases of $h = 300, 400,$ and $500 \, \text{nm}$. From Fig. 9 one sees that the optimal width $w_0$ increases as the separation $D$ increases.
$w_0$ increases when the separation $D$ increases. The value of $w_0$ decreases slightly when the height of the core increases.

3. Conclusion

In this paper we have characterized nano-Si rectangular waveguides by using a full-vectorial FDM. First the single-mode condition was determined, and it was shown that the width and height for a single-mode Si waveguide should be several hundred nanometers or less. The polarization characteristics of a nano-Si rectangular waveguide were analyzed, and the birefringence was shown to be adjustable by controlling the thickness of the cladding. For a bent nano-Si rectangular waveguide the pure bending loss is very small even for an ultrasmall bending radius, and the transition loss is dominant. For a fixed width a minimal bending radius exists so that the total loss is no more than 0.1 dB for both polarizations and the PDL is small enough. By plotting a curve of this minimal bending radius as the width varies, we have determined the optimal width with the minimal bending radius. We have also considered the coupling between two parallel nano-Si rectangular waveguides. It has been shown that an optimal width $w_0$ of a nano-Si rectangular waveguide exists, corresponding to a maximal decoupled separation distance (i.e., a maximal integration density). The slope of the curve for $L_c$ (as a function of $w$) is zero at $w = w_0$, and thus the fabrication tolerance to the optimal width is also good. These characteristic analyses are useful for the design of the PLC devices (such as an arrayed waveguide grating based on nano-Si rectangular waveguides).

This work was supported by the provincial government of Zhejiang Province of China under grants 20044131095 and R 104154.

References

Comparative study of the integration density for passive linear planar light-wave circuits based on three different kinds of nanophotonic waveguide

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A theoretical analysis and comparison of the integration density are given for passive planar lightwave circuits based on three different kinds of nanophotonic waveguide, namely, photonic crystal waveguides, Si nanowire waveguides, and nanoslot waveguides. Two criteria for determining the integration density are used. One is the minimal decoupled separation between two parallel nanophotonic waveguides, and the other is the area occupied by a low-loss 90° turn. Some important functional components (such as Y branches and optical add–drop filters) are also chosen as basic elements to evaluate the integration density. It is shown that the integration densities of passive linear planar lightwave circuits based on these three kinds of nanophotonic waveguide are comparable. © 2007 Optical Society of America

OCIS codes: 130.3120, 060.1810.

1. Introduction

Nanophotonic waveguides and devices are becoming more and more attractive because of their ultrasmall size and the possibility of realizing large-scale monolithic integration.1–7 Three interesting kinds of nanophotonic waveguide, Si nanowire waveguides1–3 (usually fabricated with a silicon-on-insulator wafer), photonic crystal (PhC) waveguides,4 and nanoslot waveguides,5 have been demonstrated. Some comparisons between them have been made concerning fabrication processes, propagation losses, etc.1 However, there is little theoretical research comparing their potential for high integration density.

People usually use the ratio of the power in the core of a waveguide, the effective width, or the minimal bending radius as the criterion to evaluate the waveguide confinement or the integration density for passive linear planar light-wave circuits (PLCs). However, these criteria are not always appropriate, especially for comparison of different types of waveguide. Recently the packaging densities of conventional waveguides and photonic crystal waveguides were compared by calculating the coupling between two parallel 1D (slab) waveguides.6 Here we give two criteria for in-depth evaluation of the integration density (particularly for passive linear PLCs) and give a comparison for different types of 2D nanophotonic waveguide (including Si nanowire waveguides, 2D PhC waveguides, and nanoslot waveguides).

For most cases of nanophotonic devices, the coupling between adjacent waveguides should be minimized by choosing a large enough separation. The separation for negligible coupling is the so-called decoupled separation, which determines how close adjacent waveguides can be placed. Therefore the decoupled separation is used as one of the criteria for evaluating the integration density in this paper. For PLCs bending waveguides are indispensable for alternating the propagation direction or introducing a phase delay. For Si nanowire waveguides and nanoslot waveguides there is a small bending radius (about several micrometers) for an acceptable bending loss.7 Theoretically speaking, for PhC waveguides a corner bending with a low bending loss can be realized. If one evaluates the integration density by directly using the criterion of the minimal bending radius, the PhC waveguides will provide the highest integration density among the three types of waveguide. However, this criterion is not fair, since the total number of periods should be large enough to obtain a PhC with a...
bandgap. These periods of poles, or pillars, occupy some area. Therefore we use the area occupied by a 90° turn as the second criterion for evaluating the integration density. With these two criteria, a larger integration density requires a waveguide with a smaller decoupled separation and a smaller area occupied by a 90° turn.

In this paper we give a theoretical comparison for three kinds of nanophotonic waveguide and conclude which kind of nanophotonic waveguide can provide the highest integration density according to these two criteria. We also compare the integration density of some basic functional elements (such as Y branches and optical add-drop filters) realized by different nanophotonic waveguides.

2. Structures of Nanophotonic Waveguides and Two Criteria

A. Decoupled Separation

Figure 1 shows the three kinds of nanophotonic waveguide with the same core height $h_{co}$. Since only the TE-polarized mode is supported in the PhC waveguides, we consider TE polarization for the comparison in this paper.

The criterion of the decoupled separation $s_{d}$ is used to determine how close two parallel waveguides can be placed for negligible coupling. The cross talk (CT) due to coupling is given by

$$CT = 10 \log_{10} \left[ \sin \left( \frac{\pi}{2} \frac{l_{0}}{L_{e}} \right) \right]^{2}, \quad (1)$$

where $l_{0}$ is the propagation distance and $L_{e}$ is the coupling length, which is dependent on separation $s$ and the parameters of the waveguides. A larger separation $s$ gives a larger coupling length $L_{e}$ and thus introduces a smaller cross talk after a propagation distance of $l_{0}$. Usually a cross talk smaller than $-30$ dB is negligible. Therefore in this paper the separation corresponding to the case with a cross talk of $-30$ dB (after a propagation distance of $l_{0}$) is taken as the decoupled separation. This means that negligible cross talk (less than $-30$ dB) is obtained when one chooses a separation larger than the decoupled separation $s_{d}$. Here we choose $l_{0} = 1$ cm as an example, since the length of two parallel nanophotonic waveguides is usually no more than 1 cm. To determine the decoupled separation from the above definition, first we calculate the coupling lengths $L_{e}$ and the corresponding cross talk from Eq. (1) for two given parallel waveguides with different separations, and then we plot the curve of the cross talk as the separation increases. From the curve, one can determine the value of the decoupled separation (i.e., that corresponding to a cross talk of $-30$ dB).

For Si nanowires or nanoslot waveguides, the coupling length of two parallel waveguides can be easily estimated by the formula $L_{e} = \pi / (\beta_{o} - \beta_{e})$, where $\beta_{o}$ and $\beta_{e}$ are, respectively, the propagation constants of the odd and even supermodes and can be calculated by using a full-vectorial finite-difference method (FV-FDM).

For two parallel PhC waveguides [as shown in Fig. 1(a)] we can calculate the dispersion curves $a/\lambda \sim k_{a}/2\pi$ by using a plane-wave expansion method for a chosen ratio $2r$ of hole diameter $D$ to period $a$ (i.e., $2r = D/a$). Figure 2 shows an example of our calculated dispersion curves with a decoupling point (the parameters of the PhC waveguides are the same as those used in Section 3). Since a decoupling point exists where the coupling length is infinite, we define the minimal coupling length in the wavelength window of [1500, 1600] nm as the coupling length of two parallel PhC waveguides. First, from the calculated dispersion curves of the two parallel PhC waveguides, one can obtain the propagation constants ($\beta_{o}$ and $\beta_{e}$) of two modes for a given $a/\lambda$ and then calculate the coupling length $L_{e}$ as $L_{e} = \pi / (\beta_{o} - \beta_{e})$. An optimal value $a_{o}$ can be obtained for a maximal coupling length at the central wavelength $\lambda_{o}$ from the dispersion curves. Then choose $a = a_{o}$ and obtain the minimal value $L_{e}(\lambda_{o})$ of coupling lengths in the wavelength window of [1500, 1600] nm. This

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minimal value \( L_{\text{min}} \) is defined as the coupling length of two parallel PhC waveguides. Then the cross talk is calculated by using Eq. (1).

B. Area A Occupied by a 90° Turn

For PhC waveguides, a sharp corner turn with low loss can be realized because of the bandgap characteristic. However, the total number of periods should be large enough to form a bandgap structure, and the loss of a 90° turn decreases as the total number of periods increases. The minimal area of a 90° turn based on PhC waveguides is given by

\[
A = (2i, a)^2, \tag{2}
\]

where \( a \) is the period and \( i \) is the required number of periods for a low loss (<0.1 dB).

For Si nanowire waveguides or nanoslot waveguides, the occupied area of a 90° turn is given by

\[
A = R^2, \tag{3}
\]

where \( R \) is the bending radius. The minimal bending radius \( R_{\text{min}} \) is defined as the bending radius corresponding to a total bending loss of 0.1 dB. For a 90° bending waveguide connected with two straight waveguides at the ends, the total loss is \( L_s + 2L_r \), where \( L_s \) is the pure bending loss and \( L_r \) is the transition loss due to mode mismatching. For a \( \pi \)/2 bent waveguide with a bending radius \( R \), the pure bending loss \( \tilde{L}_s \) is given by \( \tilde{L}_s = 20 \log \exp[(\pi/2)\beta, a R] \) (dB/90°), where \( \beta \) is the imaginary part of the propagation constant. The transition loss can be calculated by overlapping the eigenmodal field distributions of the straight and bending sections. The propagation constant and eigenmodal field distributions are calculated by using a FV-FDM in this paper.

C. Size of Functional Elements

A Y branch is one of the most important basic elements for PLCs, and its size is determined by the decoupled separation and the area occupied by the bending section. Therefore we choose it as an example for comparison of the integration density among the three kinds of nanophotonic waveguide.

For a Y branch based on PhC waveguides, as shown in Fig. 3(a), the size is given by

\[
S = (2i_d a)(2i_b a) = 4i_d l_b a^2, \tag{4}
\]

where \( i_d \) is the period number corresponding to the decoupled separation \( s_{\text{dc}} \) (i.e., \( s_{\text{dc}} = i_d a \)) and \( l_b \) is the period number required for a low turning loss.

Considering the area needed at each side of the structure to avoid interference with other waveguides, the size of a Y branch based on Si nanowire waveguides is given by

\[
S = (2s_{\text{dc}})L, \tag{5}
\]

where the S-bend length \( L \) is given by \( L = [2s_{\text{dc}} R_{\text{min}} - (s_{\text{dc}}/2)^2]^{1/2} \) from a geometric relation as shown in Fig. 3(b). Theoretically speaking, the loss in the designed Y branch based on any one of these three kinds of nanophotonic waveguide should be very small, since the designed bending has very low loss (which is the dominant source for the total loss of a Y branch). This indicates that the Y branches based on different types of nanophotonic waveguide have similar theoretical performance. Therefore we do not consider the small difference between the performances of Y branches, and we compare only the total sizes calculated by Eqs. (4) and (5).

The add–drop filter is another important basic element. For optical add–drop filters based on Si nanowire waveguides, the total size is determined by the minimal bending radius \( R_{\text{min}} \) and the decoupled separation \( s_{\text{dc}} \), i.e., \( S \approx (2R_{\text{min}} + s_{\text{dc}})^2 \). For optical add–drop filters in PhCs, the total size is determined by the decoupled separation, i.e., \( S \approx (2s_{\text{dc}})^2 \) (see the structure shown in Ref. 10).
In the following section we evaluate the integration densities of these three kinds of nanophotonic waveguide by comparing the decoupled separations, the occupied area of a 90° turn, and the total size of functional elements (such as Y branches and add–drop filters).

3. Results and Discussion

Previous study has shown that a larger height of the Si core layer can result in a larger coupling length\(^7\) (i.e., a smaller cross talk, a smaller decoupled separation, and thus a larger integration density). For the comparison in this paper, we choose the height of the Si core layer to be \(h_{\text{co}} = 300\, \text{nm}\) so that the nanophotonic waveguides can be still quasi single mode even for a case with a relatively large core width (e.g., \(w_{\text{co}} = 500\, \text{nm}\)). The refractive indices of the core (Si) and insulator–cladding (SiO\(_2\)) are 3.455 and 1.46, respectively. The central wavelength is 1.55 \(\mu\text{m}\).

A. Decoupled Separation \(S_{\text{dc}}\) between Two Parallel Waveguides

According to the description in Section 2, we can achieve an optimal design of two parallel PhC waveguides to obtain minimal cross talk (calculated by using Eq. (1)) as follows. First we choose different ratios \(2r = 0.5, 0.45, 0.4, 0.35, 0.3, 0.25, 0.2\), and the corresponding optimal values of period \(a_{\text{o}}\) for achieving a minimal cross talk are \(a_{\text{o}} = 0.578, 0.620, 0.660, 0.694, 0.720, 0.736, 0.744\, \mu\text{m}\), respectively. For these optimal-period \(a_{\text{o}}\), Fig. 4 shows that the cross talk (in decibels) of two parallel PhC waveguides decreases almost linearly as the separation \(s (=ia_{\text{o}})\) increases. For the same separation \(s\), the cross talk for the case of \(2r = 0.45\) is minimal, which corresponds to a minimal decoupled separation. From the curve of \(2r = 0.45\) in Fig. 4, the decoupled separation (for \(l_{\text{g}} = 1\, \text{cm}\)) is about 6.82 \(\mu\text{m}\) (corresponding to 11 periods, i.e., \(i_{\text{dc}} = 11\)) according to the definition in Section 2.

Figure 5(a) shows the cross talk [calculated by using Eq. (1)] as the core width of the Si nanowire waveguides increases for different separations. One sees that there is an optimal core width for minimal cross talk when the separation \(s\) is fixed (as shown in Ref. 7). A smaller cross talk can be obtained for a larger separation \(s\), as expected. According to the definition in Section 2, we obtain the decoupled separation for different core widths as shown in Fig. 5(b). Usually one chooses the core width in the range of \([460, 520]\) nm for a quasi-single-mode nanowaveguide, and the corresponding decoupled separation (for \(l_{\text{g}} = 1\, \text{cm}\)) is less than 1.7 \(\mu\text{m}\).

For nanoslot waveguides, we first choose the slot width \(w_{\text{s}} = 40\, \text{nm}\) as an example. Figure 6(a) shows the cross talk as the core width increases for different separations. Figure 6(b) shows the decoupled separations for different core widths obtained from Fig. 6(a). From this figure, one sees that the decoupled separation decreases from 2.96 to 1.96 \(\mu\text{m}\) when the core width increases from 160 to 400 nm. The minimal decoupled separation (for \(l_{\text{g}} = 1\, \text{cm}\)) is about 1.96 \(\mu\text{m}\) when the core width is chosen in the range of

![Figure 4](image1.png)

**Fig. 4.** (Color online) Cross talk for PhC waveguides as the separation \(s\) increases.

![Figure 5](image2.png)

**Fig. 5.** (Color online) For two parallel Si nanowire waveguides, (a) the cross talk as the core width varies, (b) decoupled separation for different core widths \((l_{\text{g}} = 1\, \text{cm})\).

![Figure 6](image3.png)

**Fig. 6.** (Color online) For two parallel nanoslot waveguides when \(w_{\text{s}} = 40\, \text{nm}\), (a) the cross talk as the core width varies, (b) the decoupled separation for different core widths \((l_{\text{g}} = 1\, \text{cm})\).
nanowires [320, 400] nm. For the choice of core width, one also needs to consider the single-mode condition and the minimal bending loss, as discussed below.

For nanoslot waveguides, our calculations have shown that the cross talk decreases (i.e., the decoupled separation decreases) as the slot width $w$ decreases. However, it is difficult to fabricate a very narrow slot. In fact, a nanoslot waveguide can be regarded as a special variation of a nanowire waveguide, i.e., a nanoslot waveguide becomes a nanowire waveguide when the slot width decreases to zero. Therefore the minimal decoupled separation of two nanoslot waveguides is always larger than that of nanowires when the same core height is chosen. From this comparison, one sees that Si nanowire waveguides can provide a higher integration density than nanoslot waveguides in terms of the decoupling length. This conclusion will be further confirmed by the following analysis of bending loss. One should also note that a nanoslot waveguide was proposed for enhancing the field interaction with low-index materials by sacrificing the integration density.

B. Area $A$ Occupied by a 90° Turn

1. Photonic Crystal Waveguides

We use an effective index method and a 2D finite-difference time-domain (FDTD) method\textsuperscript{11,12} to simulate the light propagation in a 90° turn PhC waveguide and estimate the turning loss from the calculated power. Here the effective index of the core is 3.0286, and we choose $a = 0.620 \mu$m and $2\sigma = 0.45$, which corresponds to the optimal case for a minimal decoupled separation of two parallel PhC waveguides. Figure 7 shows the turning loss as the period number $i$ increases. As mentioned in Section 2, the total number of periods should be large enough to form a bandgap structure so that a low-loss 90° turn can be realized. From Fig. 7 one sees that the turning loss decreases quickly as the period number $i$ increases. The minimal number of period is $i = 4$ for a turning loss less than 0.1 dB, and the corresponding occupied area $A$ is 33.2 $\mu$m$^2$ from Eq. (2). Note that the total loss for a 90° turn PhC waveguide usually has two parts. One is the bending loss, which is estimated by using a 2D FDTD method here. The other is the additional out-of-plane loss (which is ignored in a 2D FDTD simulation). The out-of-plane loss is usually about 2 dB.\textsuperscript{13} Therefore, the area $A$ occupied by a 90° turn PhC waveguide with an acceptable loss will be larger than the estimated value (33.2 $\mu$m$^2$) above.

2. Si Nanowire Waveguides and Nanoslot Waveguides

By using a FV-FDM, we calculate the total bending loss (including the pure bending loss and the transition loss) of a 90° turn Si nanowire waveguide for different bending radii as the core width increases. When the core width is relatively small, the pure bending loss is the dominant source of the bending loss. When the core width increases, the modal confinement of the Si nanowire waveguide is enhanced, and thus the pure bending loss decreases. On the other hand, when the core width increases to a certain value, the distortion (e.g., the shift outward) of the fundamental mode in the bent section become larger for a larger core width.\textsuperscript{7} This increases the transition loss. Therefore there is an optimal core width for a minimal total bending loss when the bending radius is fixed. This also indicates that one can obtain a minimal bending radius $R_{\text{min}}$ (corresponding to the optimal core width) for a requirement of the total loss $L_{\text{tol}} < 0.1$ dB. Figure 8 shows the minimal bending radius of Si nanowires and nanoslot waveguides as the core width varies. From this figure one sees that the minimal bending radius $R_{\text{min}}$ of Si nanowires is 2.1 $\mu$m when the core width $w_{\text{co}} = 420 \mu$m and the corresponding occupied area $A$ is 4.4 $\mu$m$^2$ according to Eq. (3). In contrast, the minimal bending radius $R_{\text{min}}$ of nanoslot waveguides is 2.9 $\mu$m [and the corresponding occupied area $A$ is 8.4 $\mu$m$^2$ from using Eq. (3)] when the core width $w_{\text{co}} = 220$ $\mu$m. By comparison of the decoupled separation and minimal bending radius, one can see that Si nanowires can provide a higher integration density than nanoslot waveguides.
C. Size of a Y Branch

For PhC waveguides, the values of \( i_w \) and \( i_i \) are 11 and 4, respectively. Therefore, the size of a Y branch based on PhC waveguides is about 67.6 \( \mu \text{m}^2 \). By using the formulas [Eqs. (4) and (5)] given in Section 2, we calculate the size of a Y branch based on nanophotonic wires and nanoslot waveguides, respectively. Figure 9 shows the corresponding sizes of Y branches as the core width increases. When nanophotonic wires and nanoslot waveguides are used, the minimal sizes are about 8.9 and 15.3 \( \mu \text{m}^2 \), respectively, which are smaller than a PhC-based Y branch. From the above analysis and comparison, one sees that the sizes of a Y branch based on different nanophotonic waveguides are comparable.

In addition to the Y branch, we also consider the package density of optical add–drop filters as another important basic functional component that can be realized by using either cavities in photonic crystals or microring resonators based on Si nanowire waveguides. For an add–drop filter in PhCs, the total size is usually about several hundreds of \( \alpha^2 \). For example, in Ref. 10 the size is about 300 \( \alpha^2 \), i.e., 115 \( \mu \text{m}^2 \), if one chooses \( \alpha = 0.62 \mu \text{m} \) (as a typical case). For microring resonators based on Si nanowire waveguides, the total size is about (2\( R_{\text{min}} + s_{\text{dc}} \))^2 \( \mu \text{m}^2 \) when one chooses \( R_{\text{min}} = 2.0 \mu \text{m} \), \( s_{\text{dc}} = 1.66 \mu \text{m} \). In Ref. 2 the authors demonstrated a fabricated microring resonator with a size of about 144 \( \mu \text{m}^2 \), which is comparable with the size (115 \( \mu \text{m}^2 \)) of the add–drop filter in PhCs. From the above comparison, one sees that the integration densities of passive linear PLCs based on these three kinds of nanophotonic waveguide are comparable.

4. Conclusion

In this paper we have used two criteria to compare the integration density of passive linear PLCs realized by three different kinds of nanophotonic waveguide (i.e., PhC waveguides, Si nanowire waveguides, and nanoslot waveguides). One criterion is the minimal decoupled separation, and the other is the minimal area occupied by a 90° turn with a low loss of 0.1 dB. We have also chosen a Y branch as the element for the comparison of integration density. If one considers the integration density of active components, some more complex criteria may be needed. Our simulation results have shown that Si nanowire waveguides can provide the highest integration density for passive linear PLCs. But the integration densities of passive linear PLCs based on these three kinds of nanophotonic waveguide are comparable. PhCs have their own advantages due to their properties of bandgap and strong dispersion (e.g., compact components can be realized when dispersive effects or low group velocity are required).

This project was supported by the China Postdoctoral Science Foundation (grant 2005038018), research grants (20061343 and 20051321B14) of the Zhejiang Province of China, and the National Science Foundation of China (grant 60607012).

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Numerical analysis of silicon-on-insulator ridge nanowires by using a full-vectorial finite-difference method mode solver

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Received July 16, 2007; accepted September 2, 2007; posted September 25, 2007 [Doc. ID 85306]; published October 29, 2007

The characteristics of silicon-on-insulator (SOI) ridge waveguides are analyzed by using a cylindrical full-vectorial finite-difference method mode solver with a perfectly-matched layer treatment. First, the single-mode condition for an SOI ridge nanowire with different Si core thicknesses is obtained. The obtained single-mode condition is different from that for the conventional micrometrical SOI ridge waveguides with a large cross section. By adjusting the cross section (the core width and the etching depth), one can have a nonbirefringent SOI ridge nanowire. The analysis on the bending loss of SOI ridge nanowires shows that one can have a relatively small bending radius even with a shallow etching (i.e., a small ratio y between the etching depth and the total thickness). For example, even when one chooses a small ratio y=0.4, one still has a low bending loss with a small bending radius of 15 μm for an SOI nanowire with a thin core thicknesses at 250 nm, which is very different from a conventional large SOI ridge waveguide. © 2007 Optical Society of America

OCIS codes: 130.3120, 060.4230

1. INTRODUCTION

In recent years, the silicon-on-insulator (SOI) platform has been one of the most attractive choices to realize nanophotonic wires and ultrasmall planar light wave circuit (PLCs) [1]. There have been developed various Si-nanowire-based photonic integrated devices, such as directional couplers [2,3], multimode interference (MMI) couplers [4,5], Mach–Zehnder interferometers (MZIs) [6], arrayed-waveguide grating (AWG) (de)multiplexers [7,9], and microring/disk resonators [10]. The work of most published papers was focused on SOI rectangular nanowires, which have an undercut Si core layer (i.e., some of the SiO2 insulator layer beneath the Si core layer is etched). However, this will introduce some drawbacks, such as preventing integration with active electronic functionalities e.g., metal-oxide-semiconductor (MOS) transistors or active elements with p-n junctions [1,11–13].

There are some theoretical analyses for SiO2 nanofibers [14] and SOI rectangular nanowires [15]. However, little has been reported so far on the characteristic analysis of SOI ridge nanowires. In our previous work [16], we have given detailed analyses on the characteristics of SOI ridge waveguides with large cross sections, including the bending loss and the birefringence. In this paper, we use a full-vectorial finite-difference method (FDM) with a perfectly matched layer (PML) treatment [17] for the mode calculation of SOI ridge nanowires, including the single-mode condition, the birefringence, and the bending loss, which are different from the case of large SOI ridge waveguides.

2. STRUCTURE AND ANALYSIS

Figure 1 shows the cross section of an SOI ridge nanowire, which has an SiO2 insulator layer, an Si core, and an air cladding. Usually the SiO2 buffer layer is sufficiently thick (>1 μm) to avoid the leakage to the Si substrate [18]. The refractive indices of the Si core and the SiO2 insulator layer are \( n_{Si} = 3.455 \) and \( n_{SiO2} = 1.46 \), respectively. For the analysis given below, we consider a specific wavelength \( \lambda = 1550 \) nm. A full-vectorial FDM is used to calculate the propagation constants and the field distributions of the eigenmodes for the SOI ridge nanowires and thus the single-mode condition, the birefringence, and the bending loss are analyzed. Since the layer thicknesses (e.g., \( h_{Si} \) and \( h_{SiO2} \)) may be very different, we use nonuniform grid sizes to avoid a too large memory size. The grid used is fine to have accurate results and the PML thicknesses at x and y directions are approximately 0.5 μm.

A. Single-Mode Condition

The single-mode condition is one of the most important things for the design of optical waveguides to avoid any undesirable effects (e.g., the cross talk in an arrayed waveguide grating [19]) due to higher-order modes. In one of our previous papers [15], the single-mode condition for an Si rectangular nanowire is given by a curve relating the core height and the core width (i.e., a critical boundary under which the single-mode region lies). Unlike an Si rectangular nanowire, the SOI ridge nanowire considered in this paper has more geometrical parameters, such
Therefore, in this paper one of the cutoff conditions for $P$ mode, layer. However, the case is very different for an SOI ridge $P$ first higher-order mode is cut off by using the condition $w$ [e.g., see the field distribution $P$ loss to the substrate. Therefore, besides the condition this case the first higher-order mode has a large leakage the refractive index $w$ of the Si core layer is very thin (only several hundred micrometers) and thus the characteristics are sensitive to the Si thickness. Therefore, here we consider the cases with different core heights ($h_{co}=250, 300, 350, 400, 450, and 500$ nm).

For an SOI rectangular nanowire, the single-mode–multimode boundary can be easily determined by the condition that the higher-order mode has an effective index lower than the refractive index $n_{SiO_2}$ of the SiO$_2$ insulator layer. However, the case is very different for an SOI ridge nanowire. Even when the higher-order order is close to be cut off, the effective index is usually still much larger than the insulator index $n_{SiO_2}$. Consequently we should use a different criterion for the determination of the single-mode–multimode boundary (i.e., the cut-off condition of the first higher-order mode). We note that when the eigenmode is close to the cutoff most of the power is confined in the slab region instead of the ridge core region [e.g., see the field distribution $E_{21}(x,y)$ given in Fig. 2(e)]. Therefore, in this paper one of the cutoff conditions for the higher-order mode is given by $P_{co} < P_{co0}$, where $P_{co}$ is the power confined in the ridge area for a higher-order mode, $P_{co0}$ is a given value. Here we choose $P_{co0} = 0.05$, which gives a relatively critical single-mode condition. If choosing a larger $P_{co0}$, one will have a relaxed single-mode condition. We also note that in some cases the first higher-order mode has relatively large confined power $P_{co} > P_{co0}$ while the effective index is much smaller than the refractive index $n_{SiO_2}$ of the SiO$_2$ insulator layer. In this case the first higher-order mode has a large leakage loss to the substrate. Therefore, besides the condition $P_{co} < P_{co0}$ in this paper we use an additional requirement for the cutoff condition of the first higher-order mode, i.e., the leakage loss $L_{lk}$ is larger than 200 dB/mm. Such a condition guarantees that the cross talk due to the higher-order modes is smaller than −20 dB after a distance of 100 μm (which is the typical order of the length for an Si nanowire device).

For each case with a given core height, we scan the core width $w_{co}$ and the ridge height $h_r$, and check whether the first higher-order mode is cut off by using the condition $P_{co} < P_{co0}$ and $L_{lk} > 200$ dB/mm. For a fixed ratio $\gamma = h_r / h_{co}$, the cut-off width $w_{cutoff}$ is obtained by reducing the core width $w_{co}$ with a step of 20 nm until the first higher-order mode is cut off. Figures 2(a) and 2(b) show the cutoff width $w_{cutoff}$ of the first higher-order TE and TM modes for cases with different core heights $h_{co}$ as the ratio $\gamma$ increases. The curve indicates the critical boundary under which the single-mode region lies. From this figure, one can easily choose the core width for a single-mode SOI ridge nanowire when the core height $h_{co}$ and the ratio $\gamma$ are given. Since the SOI ridge nanowire is strongly polarization dependent, the single-mode conditions for the TE and TM modes are very different [as shown in Figs. 2(a) and 2(b)]. From Figs. 2(a) and 2(b), one also sees that the single-mode conditions are very different when the core height $h_{co}$ increases from 250 to 500 nm. Here we give a detailed explanation for the case of TE mode as follows (one can get a similar analysis for the TM mode).

For the TE mode, when the SOI ridge nanowire has a small core height (e.g., $h_{co}$ = 250 nm), the first higher-order mode is $E_{21}(x,y)$ (which has two peaks at the horizontal direction and one peak in the vertical direction). In this case, the single-mode conditions given in Fig. 2(a) correspond to the cutoff boundary for the mode $E_{21}(x,y)$. However, for the case with a large core height (e.g., $h_{co}$ = 500 nm), the first higher-order mode will be alternated from $E_{21}(x,y)$ to $E_{12}(x,y)$ (which has one peak at the horizontal direction and two peaks in the vertical direction) as the ratio $\gamma$ increases. This can be observed in Figs. 2(d) and 2(e). In this case, the single-mode condition is given by the smaller one between the cutoff widths for the modes of $E_{21}(x,y)$ and $E_{12}(x,y)$. For example, Fig. 2(e) shows the cutoff widths for the modes of $E_{21}(x,y)$ and $E_{12}(x,y)$ as the ratio $\gamma$ increases from 0.4 to 1.0 when $h_{co}$ = 500 nm. When $\gamma$ = 1.0, the SOI ridge nanowire becomes an Si rectangular nanowire (whose single-mode condition is given in [15]). To make it understood better, in Figs. 2(d) and 2(e) we demonstrate the field distributions of the fundamental mode and the first higher-order mode for both polarizations in the present SOI ridge nanowires with $h_{co}$ = 500 nm when $(\gamma, w_{co}) = (0.6, 0.66 \mu m), (0.8, 0.4 \mu m)$, respectively [see points A, B in Fig. 2(a)]. From these figures, one sees that the first higher-order TE mode is $E_{21}(x,y)$ when $\gamma = 0.6, 0.66 \mu m$ and the higher-order TE mode becomes $E_{12}(x,y)$ when $\gamma = 0.8, 0.4 \mu m$. Since the higher-order TE mode is close to the cutoff boundary for the current case [see Fig. 2(a)], the modal field extends to the slab region remarkably [see $E_{21}(x,y)$ in Fig. 2(d)]. In contrast, the field distributions of the TM modes have very different results. The first higher-order TM mode is $E_{21}(x,y)$ for both cases and far away from the cutoff boundary. This is why the single-mode condition is seriously polarization dependent [as shown in Figs. 2(a) and 2(b)].

Figure 2(a) also shows that when the ratio $\gamma$ is relatively small (e.g., $\gamma < 0.7$) the SOI ridge nanowire with a larger core height has a larger cutoff width $w_{cutoff}$ for the first higher-order mode. For example, when one chooses $\gamma = h_r / h_{co} = 0.5$, the cutoff widths $w_{cutoff}$ are approximately 0.7 and 0.56 μm for the cases of $h_{co}$ = 500 and 250 nm, respectively, which looks unreasonable. Actually, this can be explained qualitatively as follows. Although an effective...
Fig. 2. (Color online) (a) Single-mode conditions of the TE mode for Si ridge nanowires with different core heights; (b) single-mode conditions of the TM mode for Si ridge nanowires with different core heights; (c) cutoff width of the higher-order TE modes in an Si ridge nanowire when $h_{co} = 500$ nm; (d) field distributions of the fundamental mode and the first higher-order mode when $h_{co} = 500$ nm, $\gamma = 0.8$, $w_{co} = 0.4$ $\mu$m; (e) field distributions of the fundamental mode and the first higher-order mode when $h_{co} = 500$ nm, $\gamma = 0.8$, $w_{co} = 0.4$ $\mu$m.
index method (EIM) is not accurate for SOI nanowires, we would like to use it for a qualitative analysis. By using an EIM, an SOI ridge nanowire can be equivalent to a slab waveguide with a refractive index contrast \( \Delta n = n_{\text{eff, co}} - n_{\text{eff, cl}} \), where the indices \( n_{\text{eff, co}} \) and \( n_{\text{eff, cl}} \) of the core and the cladding are determined by the thicknesses of the core height \( h_{\text{co}} \) and the slab height \( h_{\text{slab}} \), respectively. Here we consider the TE and TM fundamental modes, i.e., the difference between the effective refractive indices of the larger index contrast is close to 1, a larger core height introduces a larger index contrast \( \Delta n \) and thus a larger cutoff width \( w_{\text{cutoff}} \) when the core height \( h_{\text{co}} \) is smaller. When the ratio is close to 1, a larger core height introduces a larger index contrast \( \Delta n \) (see Fig. 3) and consequently a smaller cutoff width [see Fig. 2(a)]. Furthermore, when one chooses a small \( \gamma \) for some specific designs, a small core height (e.g., \( h_{\text{co}} = 250 \) nm) is preferred to achieve a small bending radius (which will be discussed more in Subsection 2.C).

B. Birefringence

The birefringence \( B \) of an optical waveguide is defined as the difference between the effective refractive indices of the TE and TM fundamental modes, i.e., \( B = n_{\text{TE}} - n_{\text{TM}} \). Usually the birefringence mainly results from the anisotropy of the refractive index distribution due to the geometrical asymmetry or the stresses [20]. For the present SOI ridge nanowire with an air cladding, the birefringence is mainly introduced by its geometrical asymmetry.

Figures 4(a)–4(f) show the geometrical birefringence \( B \) of SOI ridge nanowires with different ratios \( \gamma \) for the cases of \( h_{\text{co}} = 500, 450, 400, 350, 300, \) and 250 nm, respectively, as the core width \( w_{\text{co}} \) increases. From these figures, one sees that the birefringence of an SOI ridge nanowire is usually very large (at the order of \( 10^{-2} \)) when the cross section is not designed optimally. Therefore, an Si-nanowire-based PLC device without an optimal design usually has a serious polarization dependency [8].

In Figs. 4(a)–4(f), we consider only SOI ridge nanowires with a ridge width ranging from larger than 250 nm to \( h_{\text{co}} + 100 \) nm. When the ridge width \( w_{\text{co}} \) is very large, the SOI waveguide behaves like a slab waveguide (with thickness \( h_{\text{co}} \) for the guiding core layer) and thus has a positive birefringence. Thus, for any value of \( \gamma \), the birefringence approaches the same positive value (i.e., the birefringence for a slab waveguide of thickness \( h_{\text{co}} \) when \( w_{\text{co}} \) becomes very large (see the curves in Figs. 4(a)–4(f)). This is similar to that for a conventional SOI ridge waveguide with a large cross section [16].

When the ridge width \( w_{\text{co}} \) is very small (approaches zero), the SOI ridge nanowire should behave like a slab waveguide with a thickness \( h_{\text{slab}} \) (other than \( h_{\text{co}} \)). Therefore, in this case the birefringence of the SOI rib waveguide also tends to a positive value. This has been observed in a conventional SOI ridge waveguide. For SOI ridge nanowires, however, the fundamental mode may be cut off when the ridge width is very small. Therefore, in Figs. 4(a)–4(f), the design with a small ridge width and a positive birefringence is not shown.

From these figures, one sees that in most cases the birefringence monotonously varies from a positive value to a negative one when the ridge width decreases from \( h_{\text{co}} + 100 \) nm [see the curves of \( h_{\text{co}} = 350, 300, \) and 250 nm shown in Figs. 4(a)–4(f)]. In this case, one obtains an optimal ridge width \( w_{\text{co}} \), for a zero-birefringent SOI ridge nanowire. For the case with a relatively large \( h_{\text{co}} \) (e.g., \( h_{\text{co}} > 400 \) nm), one can see that there is a nonmonotonous variation of the birefringence as the ridge width decreases from \( h_{\text{co}} = 100 \) to 250 nm [see the curve of \( h_{\text{co}} = 500 \) nm and \( \gamma = 0.72 \) in Fig. 4(a)]. When the ridge width decreases further, a positive birefringence appears as the explanation and two zero-birefringent points \( w_{\text{co1}}, w_{\text{co2}} \left( w_{\text{co1}} > w_{\text{co2}} \right) \) can be obtained. Considering the desirability of a good mode confinement, the large nonbirefringent ridge width \( w_{\text{co1}} \) is preferred.

Figure 5 shows the nonbirefringent ridge width \( w_{\text{co1}} \) for the cases with different core heights as the ratio \( \gamma \) increases. From this figure, one can easily choose the optical ridge width \( w_{\text{co}} \) the ratio \( \gamma \), and the core height \( h_{\text{co}} \) for a nonbirefringent SOI ridge nanowire. We also note that the fabrication tolerance is very small. For example, the variation of the ridge width should be as small as 1 nm [21] when a birefringence smaller than \( 10^{-4} \) is required. Therefore, in order to obtain a polarization-insensitive PLC device based on optimal SOI ridge nanowires, the fabrication should be controlled carefully to minimize the geometrical birefringence due to the fabrication-induced deformation of the cross section. Then the minimized geometrical birefringence can be compensated by introducing a postcompensation process (e.g., the thermal oxidation [20]).

On the other hand, this large birefringence of SOI ridge nanowires makes it possible to design a compact polarization splitter (e.g., based on a MZI). From Figs. 4(a)–4(f), one sees that a small variation of the core width will modify the birefringence greatly due to the small cross section and the strong confinement. For example, when \( h_{\text{co}} = 500 \) nm and \( \gamma = 1 \), the birefringence is reduced from \( -0.7 \) to \( -0.23 \) by increasing the ridge width from 250 nm to 350 nm. In this case, it is possible to design an ultrashort polarization splitter by using an asymmetrical MZI including two arms with different widths.

C. Bending loss

The bending loss includes the pure bending loss and the transition loss. The pure bending loss \( L_p \) is given by \( L_p = 20 \log \left[ \exp \left( -\pi/2\beta L_t R \right) \right] \) (dB), where \( R \) is the bending radius, \( \beta_t \) is the imaginary part of the propagation constant.
The transition loss is estimated by overlapping the fundamental modal fields of the straight section and the bending section [22]. Both the propagation constants $\beta$ and the modal field distributions $E(x,y)$ are obtained from a full-vectorial FDM mode solver in a cylindrical coordinate system (with a PML boundary treatment). Here the cylindrical coordinate system is used to obtain an accurate and convenient calculation of eigenmodes for bending waveguides [17]. Here we consider the TE polarization. Figure 6(a) shows the calculated pure bending loss $L_p$ of an SOI ridge nanowire with a core height of $h_{co} = 250 \text{ nm}$. From this figure, one sees that the pure bending loss increases almost exponentially as the bending radius decreases, which is similar to the case of a conventional optical waveguide. In this figure, one also sees that the bending loss decreases greatly when the ratio increases. This is because a larger ratio introduces a stronger confinement (see Fig. 3). To achieve a small bending radius for a high integration density, a large ratio $\gamma$ (i.e., a deep etching) is preferred. For example, the bending radius can be as small as 2 $\mu\text{m}$ when one chooses $\gamma = 0.9$. The bending loss can be reduced slightly by choosing a larger core width $w_{co}$. On the other hand, the core width is limited by the single-mode condition (see Fig. 1). Therefore, one should choose an appropriate core width to minimize the total bending loss and satisfy the single-mode condition.

Here we also consider the case with a thicker core (e.g., $h_{co} = 500 \text{ nm}$), and the calculated bending loss $L_p$ is shown in Fig. 6(b). From Figs. 6(a) and 6(b), one sees the cases with different thicknesses ($h_{co} = 250 \text{ nm}$ and $h_{co} = 500 \text{ nm}$) have similar pure bending losses as the ratio and the core width increase. We note that the SOI ridge nanowire with a larger core height $h_{co}$ has a smaller bending loss when the ratio $\gamma$ is very large ($\gamma > 0.9$). Here we consider the case of $w_{co} = 460 \text{ nm}$ as an example (the other case with different widths has a similar result). From Figs. 6(a) and 6(b), one sees that when $\gamma = 0.9$ the pure bending loss of a

Fig. 4. (Color online) Birefringence of an SOI ridge nanowire with different core heights and different ratios $\gamma$ as the core width increases: (a) $h_{co} = 500$, (b) $h_{co} = 450$, (c) $h_{co} = 400$, (d) $h_{co} = 350$, (e) $h_{co} = 300$, (f) $h_{co} = 250 \text{ nm}$.

Fig. 5. (Color online) Optimal core width $w_{co1}$ for a nonbirefringent SOI ridge nanowire as the ratio $\gamma$ increases.

Fig. 6. (Color online) Pure bending loss as the bending radius increases. (a) $h_{co} = 250$, (b) $h_{co} = 500 \text{ nm}$. 
bending $R=2 \mu m$ for the case of $h_{co}=250 \text{ nm}$ is very small (approximately $3.52 \times 10^{-4} \text{ dB}$) while the loss for the case of $h_{co}=500 \text{ nm}$ is even smaller (approximately $3.01 \times 10^{-5} \text{ dB}$). However, the situation is opposite when the ratio $\gamma$ becomes smaller (e.g., $\gamma<0.78$). For example, when $\gamma=0.6$, the pure bending losses of a bending $R=7.5 \mu m$ for the cases of $h_{co}=250 \text{ nm}$ and $h_{co}=500 \text{ nm}$ are $6.4 \times 10^{-5}$ and $0.37 \text{ dB}$, respectively. This is because the equivalent slab waveguide of an SOI ridge nanowire with a larger core height will have a smaller the index contrast $\Delta$ when the ratio $\gamma$ is relatively small (see Fig. 3).

Figures 7(a) and 7(b) show the transition losses for the cases of $h_{co}=250 \text{ nm}$ and $h_{co}=500 \text{ nm}$. The transition loss is estimated by using an overlapping integral method [22]. From Figs. 6 and 7, one sees that the pure bending loss increases much more rapidly than the transition loss as the bending radius decreases. For the case with a large ratio ($\gamma>0.6$), the transition loss is usually larger than the pure bending loss, which indicates that the transition loss is the dominant one of the total bending loss. Therefore, for a design with straight-bending junctions, one should pay more attention to the transition loss other than the pure bending loss. On the other hand, when one designs a bending structure without straight-bending junctions (e.g., microring resonators), one can determine the minimal bending radius according to the allowable minimal bending loss.

From the analysis of the bending loss shown in Figs. 6 and 7, we note that one can have a relatively small bending radius even with a shallow etching (i.e., a small ratio $\gamma$ between the etching depth and the total thickness). For example, for an SOI nanowire with a thin core $h_{co}=250 \text{ nm}$, the bending radius can be as small as $15 \mu m$ even when a small ratio $\gamma=0.4$ is used, which is very different from a conventional large SOI ridge waveguide.

3. CONCLUSION

In this paper, we have given a detailed analysis for the characteristics of SOI ridge nanowires by using a cylindrical full-vectorial FDM with a perfectly matched layer treatment. It has been shown that the single-mode condition of an SOI ridge nanowire is strongly polarization dependent and very different from that of a conventional SOI ridge waveguide with a large cross section. The design for nonbirefringent SOI ridge nanowires has been achieved by adjusting the cross section (the core width and the etching depth). We also have evaluated the bending loss of SOI ridge nanowires and theoretically shown that a relatively small bending radius can be achieved even with a small ratio $\gamma$ (i.e., a shallow etching). We also note that the characteristics of SOI ridge nanowires are dependent on the wavelength. Fortunately, in the window of [1500–1600] nm, the single-mode condition, the birefringence, and the bending loss do not change much. Therefore, one can choose the waveguide parameters initially from the results given in this paper.

ACKNOWLEDGMENTS

This project was supported by research grants (20061343 and 2006R10011) of the provincial government of Zhejiang Province of China, the National Science Foundation of China (60607012 and 60688401).

REFERENCES


Comparative Study of Losses in Ultrasharp Silicon-on-Insulator Nanowire Bends

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Abstract—Ultrasharp silicon-on-insulator (SOI) nanowire bends (with a bending radius of \( R < 2 \mu m \)) are analyzed numerically. It is shown that the calculated bending losses for ultrasharp bends are overestimated when using a modal analysis method based on finite-difference method. In this case, reliable estimation of the bending loss can be made with a 3-D finite-difference time-domain (3-D-FDTD) method. By using 3-D-FDTD simulation, the losses in SOI nanowire bends with different structures and parameters are studied. By increasing the core width or height of the waveguide, one can reduce the bending loss at longer wavelengths for TE mode while the bending performance at shorter wavelengths degrades due to the multimode effect. Increasing the core height is much more effective to reduce the bending loss of TM mode than increasing core width. The relationship between the intrinsic \( Q \)-factor of a microring resonator and the bending radius is also obtained.

Index Terms—Bending loss, finite-difference time domain (FDTD), nanowire, silicon-on-insulator (SOI), ultrasharp, waveguide.

I. INTRODUCTION

Optical devices based on planar lightwave circuits (PLCs) are attractive because of their excellent performances and compact sizes. Currently, there are many materials and structures available for optical waveguides. Among them, the SiO\(_2\)-buried rectangular waveguide is one of the most popular types. However, the bending radius of the SiO\(_2\)-buried rectangular waveguide is usually very large (several millimeters or centimeters) for an acceptable bending loss because of its low-refractive-index contrast \( \Delta \) (e.g., 0.45\% [1] to 2.5\% [2]), which limits the integration density of PLCs to a fairly low level.

There have been some works on achieving sharp bends previously. For example, Manolatou et al. [3] have proposed the resonant-cavity-based sharp bends to increase the bending transmission. Espinola et al. [4] have further improved the bending performance by using a corner mirror (and a double-corner mirror) combined with a phase retarder. Both of these sharp bends need relatively complicated optimization for good bending performances. Therefore, people may prefer to choose a simple bending structure with a curved waveguide, which is considered in this paper.

In recent years, silicon-on-insulator (SOI) nanowire waveguides with ultrahigh \( \Delta \) are becoming more and more attractive [5], [6]. By using SOI nanowires, it is possible to have submicrometer cross section, ultrasmall bending radius, very small decoupled separation [7], and consequently, very high integration density. Various functional devices based on SOI nanowires have been realized, such as arrayed waveguide gratings (AWGs) [8], microring resonators (MRRs) [9], and Mach–Zehnder interferometers (MZIs) [10]. Among these devices, bends are the basic element to realize various configurations and functions. Therefore, an accurate characteristic analysis for SOI nanowire bends is necessary for the design of photonic integrated devices.

There have been some published results about the bending loss of SOI nanowires based on FDM when the bending radius \( R > 2 \mu m \) [11]. It is important to determine the minimum bending radius since the footprint of a bending structure (e.g., a turn or a microring) scales down quadratically as the bending radius decreases. Furthermore, ultrasharp bends (i.e., \( R < 2 \mu m \)) are essential to realize ultracompact photonic integrated devices with some special requirements. For example, when an MRR filter with a large free spectral range (FSR; e.g., ∼40 nm) is desirable, the bending radius should be as small as 1 \( \mu m \) [12].

In order to estimate the bending loss of an optical waveguide, people usually use finite-difference method (FDM) or finite-element method (FEM) mode solver to calculate the propagation constant and the modal field distributions, and then calculate the pure bending loss and transition loss with some formulas [11], [13], [14]. These methods are creditable for the case with relatively large bending radius, but give overestimated bending loss (as found in the present paper) for the case of ultrasharp bends. Therefore, a more accurate calculation method is needed.

In order to estimate the loss in bends, one can also use some numerical methods to simulate light propagation in bends. Finite-difference time-domain (FDTD) method [15] is widely recognized as one of the most accurate numerical methods since it is directly derived from Maxwell’s equations without approximations. Usually, people use 2-D-FDTD method combined with an effective index method (EIM), which, however, is not accurate enough to quantify the practical performance in a high-index-contrast system. In this paper, we use the 3-D-FDTD method to have accurate simulation results. Even though a 3-D-FDTD method usually requires a large amount of memories and is very time-consuming, fortunately, in our case of ultrasharp
bends, the computation window is relatively small. Thus, a 3-D-FDTD simulation is possible. In the following part, we give an accurate analysis of the bending losses for ultrasharp SOI nanowire bends \((R < 2 \mu m)\) with a 3-D-FDTD method and also a comparison with the results from other numerical methods.

II. ANALYSES AND DISCUSSIONS

The SOI nanowire waveguide considered here has a silicon core \((n = 3.455)\), a SiO2 buffer layer \((n = 1.46)\), and a cladding of air \((n = 1.0)\) or SiO2 \((n = 1.46)\). The cross section of the SOI nanowire is shown in Fig. 1. A typical bending structure includes a straight input section, a 90° bending section, and a straight output section (see Fig. 2).

A. Comparison of Different Simulation Methods

For the calculation of bending loss, there exist several available methods, among which the modal analysis method (MAM; e.g., FDM [13], FEM [14]) is one of the most popular methods. Theoretically speaking, the bending loss should include the pure bending loss \(L_p\) and the transition loss \(L_t\). For a bending waveguide (as shown in Fig. 2), the peak of the modal field shifts outward, which introduces a modal mismatch between the straight section and the bending section. This consequently results in the transition loss \(L_t\), which is estimated by overlapping the fundamental modal field of the straight waveguide and that of the bending waveguide. The pure bending loss \(L_p\) can be determined by the imaginary part of the propagation constant. Then, the total bending loss of the whole bending structure (see Fig. 2) is given by \(L_{tol} = 2L_t + L_p\).

Another method is the FDTD method. In this way, one can simulate light propagation along the optical waveguide (with the launch field \(E_{in}(x, y)\) normalized to unit power), and then the power fraction \(P\) coupled to the output waveguide is obtained by using an overlap integral between the optical field \(E_{out}(x, y)\) at the output end and the normalized fundamental modal field \(E_0(x, y)\) of the output waveguide, i.e., \(P = \int \int E_{out}(x, y)E_0^*(x, y)dx\,dy\). Then the total bending loss of the whole bending structure is given by \(L_{tol} = -10\log P\).

In the following part, we give a comparison between these two methods. For the first method (e.g., MAM based on full-vectorial (FV) FDM with a perfectly-matched layer (PML) treatment [16]), the grid sizes are chosen as \(\Delta x = \Delta y = 15\) nm. For the second method (e.g., 3-D-FDTD method [15]), we choose the same grid sizes (i.e., \(\Delta x = \Delta y = \Delta z = 15\) nm). Since relatively coarse grids can be considered as an artificial grating on the bend’s sidewall and may lead to additional scattering loss for the FDTD simulation, it is necessary to investigate the convergence of the result. After checking this, we find that the variation of the results is no more than 0.1% when making the grid sizes as small as 8 nm, which indicates that the present grid
sizes ($\Delta x = \Delta y = \Delta z = 15 \text{ nm}$) are fine to obtain accurate results. Here, we designate a specific wavelength of 1.5 $\mu$m, and the waveguide parameters (with an air cladding) are $w_{co} = 450 \text{ nm}$ and $h_{co} = 220 \text{ nm}$. These parameters are the same as those in [17], so that our numerical results can be compared with their experimental results. The simulation results for TE fundamental mode are shown in Fig. 3, where we also include the experimental results of the bending loss $L$ from [17]: $L = 0.086 \pm 0.005$ dB at $R = 1 \mu$m and $L = 0.013 \pm 0.005$ dB at $R = 2 \mu$m. From this figure, one sees that the simulation results of the 3-D-FDTD method (see the solid curve in Fig. 3) agree well with the experimental data (shown by the diamonds in Fig. 3). This indicates that the 3-D-FDTD method is reliable for the calculation of the bending loss in ultrasharp bends. One also sees that the bending loss calculated with MAM (shown by the dashed curve in Fig. 3) is much larger than that calculated with the 3-D-FDTD method, especially when the bending radius $R$ is very small. For example, the bending losses of TE mode obtained with 3-D-FDTD method are 0.091 and 0.030 dB for $R = 1$ and 2 $\mu$m, respectively, while the values of the losses obtained with the MAM are 0.481 and 0.087 dB, respectively.

In order to explain why MAM overestimates the bending loss, we show the $H_y$-field distribution (of TE mode) obtained with 3-D-FDTD along the whole bending structure when $R = 0.5 \mu$m (see Fig. 4). When the launched light enters the bending section, the dominant part of the input field is coupled to the fundamental mode of the bending waveguide and the other part is coupled to some higher order modes. These higher order modes are leaky and do not propagate for a long distance. This part of field radiates outward along the bending section, as shown in Fig. 4. However, one should note that the propagation distance (i.e., $\pi R/2$) in a 90° ultrasharp bend is very short. Therefore, some part of the power coupled to the higher order modes of the bending waveguide is received by the output section before it attenuates to zero. This part of power is ignored when using MAM, which leads to the overestimation of the bending loss.

Since 3-D-FDTD method is very time-consuming and memory-intensive, as mentioned before, people usually convert a 3-D structure to a 2-D one by using the EIM and then carry out 2-D-FDTD calculations [18]. Here, we also give the simulation results of the 2-D-FDTD method with an EIM (see the dotted curve in Fig. 3). From this comparison, one sees that...
the 2-D-FDTD results are quite close to those obtained with the 3-D-FDTD method though some deviation exists. This deviation comes from the inaccuracy of the EIM when it is applied to SOI nanowire waveguides with a high index contrast. According to the earlier discussions, we use 3-D-FDTD method for all the simulations in the rest of the paper.

B. Characteristic Analysis of SOI Nanowire Bends by Using 3-D-FDTD Method

First, we consider the SOI nanowire with an air cladding and core height $h_{co} = 220$ nm (see Fig. 1). We calculate the bending losses for the cases with different core widths $w_{co}$ (=400, 450, 500, and 600 nm) as a function of wavelength. Fig. 5(a) and (b) shows the results of TE polarization for the cases of $R = 1$ and 2 $\mu$m, respectively. When there is a small core (e.g., $w_{co} = 450$ nm), for a short wavelength (i.e., $<1.5$ $\mu$m) far from cutoff, the bending loss of the TE mode is very low (<0.1 dB) and smoothly varies. However, the bending loss increases sharply at longer wavelengths (i.e., $>1.5$ $\mu$m), as shown in Fig. 5(a). With an even narrower core (e.g., $w_{co} = 400$ nm), the bending loss of wavelengths $>1.5$ $\mu$m increases more sharply because the light is even less confined in the core. When increasing the core widths (e.g., $w_{co} = 500$ and 600 nm), the bending loss decreases effectively at longer wavelengths [e.g., Fig. 5(a) and (b)] because the light confinement increases compared to the case with a narrower core.

However, both the straight and bending waveguides become multimode when there is a wide core, especially for shorter wavelengths. (The single-mode condition of the silicon nanowire waveguide can be found in [11].) In this case, when light enters the bending section, part of the power is coupled to some higher order modes of the bending waveguide, and these higher order modes are much more lossy and sensitive to bends (especially for sharp bends). Furthermore, there is more transition loss concerning the higher order modes since the mode mismatch is more serious. Consequently, larger loss is introduced at shorter wavelengths. Therefore, when the core width is too large, the bending performances of shorter wavelengths may degrade. For example, the bending loss reaches 0.3 dB at a wavelength of 1.2 $\mu$m for $w_{co} = 600$ nm when $R = 2$ $\mu$m [see Fig. 5(b)]. It is even larger than in the case of $R = 1$ $\mu$m because the field profile at the output section is dependent on the length of the bending waveguide (i.e., $\pi R/2$) as a consequence of the multimode interference effect. And this leads to different transition loss when the output field is overlapped with the fundamental mode of the output waveguide.

In order to explain the difference between the loss sources for the two cases with a small $w_{co}$ at longer wavelengths and a large $w_{co}$ at shorter wavelengths more clearly, we give the $H_y$-field distributions (of TE modes) along the whole bending structure with $R = 2$ $\mu$m when $w_{co} = 400$ nm at $\lambda = 1.7$ $\mu$m and $w_{co} = 600$ nm at $\lambda = 1.2$ $\mu$m in Fig. 6(a) and (b), respectively. For a smaller $w_{co} (=400$ nm), from Fig. 6(a), one sees that the light confinement in the waveguide is quite weak and considerable part of power radiates outward and is lost. For a larger $w_{co}$ (=600 nm), though the light is well confined in the waveguide as shown in Fig. 6(b), there are some oscillations for the peak deviation of the optical field from the central axis of the bend. This indicates the multimode effect and increases the transition loss.

For TM mode, the bending losses are very large (generally $>0.1$ dB) for the present core height when $R = 1$ and 2 $\mu$m [see Fig. 5(c) and (d)]. This indicates that merely increasing the core width is insufficient to reduce the bending loss of TM mode.

Another simple way to reduce the bending loss at longer wavelengths is to increase the core height $h_{co}$. Here, we also calculate the bending losses as a function of wavelength for the cases with different core heights $h_{co} (=220, 300, and 340$ nm) when $w_{co}$ is fixed as 450 nm. For TE mode, a larger $h_{co}$ provides similar results as a larger $w_{co}$ does [see Fig. 7(a) and (b)]. However, it is much more effective to enhance the light confinement of TM mode and reduce its bending loss by increasing $h_{co}$ than by increasing $w_{co}$. This is extremely remarkable for TM mode around $\lambda = 1.55$ $\mu$m, which is the most commonly used wavelength for optical fiber communications. This is because the cutoff TM polarization mode becomes the guided one as $h_{co}$ increases. For example, when $R = 1$ $\mu$m, the bending losses...
of TM mode at $\lambda = 1.55 \mu m$ are about 3.5, 0.24, and 0.06 dB for the case of $h_{co} = 220, 300, \text{ and } 340 \text{ nm}$, respectively [see Fig. 7(c)]. In some cases when TM operation is needed, it is necessary to reduce the bending loss of TM mode. Therefore, in order to achieve low bending losses (<0.1 dB) for both TE and TM modes when the bending radius is as small as $1 \mu m$, the core height should be larger than 340 nm [see Fig. 7(a) and (c)]. Again, for the case with a larger $h_{co}$, the bending performances at shorter wavelengths may degrade due to the multimode effect [see Fig. 7(a) and (d)].

Although the bending loss is very small in an ultrasharp bend (even with $R = 1 \mu m$) through a careful design, the polarization crosstalk may rise considerably if the waveguide sidewall is not ideally vertical. For example, the theoretical polarization crosstalk can reach around 15 dB for $R = 1 \mu m$ when the sidewall angle is $83^\circ$ [19]. This should be considered when using these ultrasharp bends.

Another potentially important issue related to these ultrasharp bends is the back-reflection problem. Our simulation results show that the reflectivity ranges from 20 to 26 dB for sharp bends with $R = 0.5–2 \mu m$ in the wavelength window of 1.2–1.7 $\mu m$. Typically, the reflection has a contribution of 5%–30% to the total bending loss, which indicates that the bending loss is mainly caused by the outward radiation.

Then the influence of different cladding materials on the bending loss is also investigated. In some cases, a SiO$_2$ layer is deposited on the silicon core to protect it from contaminations (e.g., dust) as well as to make the waveguide structure symmetric in the vertical direction [6], [20]. The bending losses for the cases with different claddings (air or SiO$_2$) are compared here. Fig. 8(a) and (b) shows the calculated bending losses for TE and TM polarizations, respectively. The Si nanowire with a core of $450 \times 220 \text{ nm}^2$ is considered. When adding a SiO$_2$ cladding, the light confinement becomes weaker, and thus, more part of the modal field extends outside the core, and consequently, the bending loss becomes larger.

The earlier analysis is concentrated on the bending structure shown in Fig. 2, which is usually used to form a turn in PLCs.

![Diagram](image_url)
In some other cases, e.g., an MRR, the bending structure is composed of only a ring waveguide without any straight waveguides. There is no transition loss in such a structure, and the pure bending loss accounts for the total bending loss. Fig. 9(a) shows the calculated pure bending loss at $\lambda = 1.55 \mu m$ for several different $h_{co}$ (with fixed $w_{co} = 450 \text{ nm}$). One sees that the pure bending loss increases exponentially as the bending radius $R$ decreases. When determining the minimum bending radius, one should consider the requirements of the designed devices. For example, for MRR, the intrinsic $Q$-factor (or unloaded $Q$-factor) is an essential parameter, which is inversely proportional to the pure bending loss [21] [as shown in Fig. 9(b)]. The intrinsic $Q$-factor is the maximum achievable $Q$-factor for an MRR. From Fig. 9(b), one can easily determine the minimum bending radius for different applications. For example, if $Q \sim 5000$ (corresponding to a $10^3$ intrinsic $Q$ when the critically coupled condition is satisfied [22]) is required for the MRR, the minimum bending radius are about 1.37, 1.13, and 1.01 $\mu m$ for the cases of $h_{co} = 220$, 300, and 340 nm, respectively. If a larger $Q$ is required, the bending radius should be increased accordingly.

III. CONCLUSION

We have analyzed ultrasharp SOI nanowire bends with $R < 2 \mu m$ by using numerical methods. It has been shown that a MAM usually overestimates the bending loss and a 3-D-FDTD method is more reliable. By using a 3-D-FDTD simulation, we have analyzed the dependence of the bending loss on the size and structure of the SOI nanowire bend. By increasing the core width or height of the waveguide, one can reduce the bending loss at longer wavelengths for TE mode, while the bending performance at shorter wavelengths degrades due to the multi-mode effect. Increasing the core height is much more effective to reduce the bending loss of TM mode than increasing the core width. When there is a SiO$_2$ cladding, the bending loss increases since the light confinement becomes weaker. The presented simulation results have shown that the bending radius of the SOI nanowire waveguide can be as small as 1 $\mu m$ (less than the wavelength of 1.55 $\mu m$) through a careful design while still maintaining low bending loss ($<0.1$ dB). This is helpful to realize high-density photonic integrated circuits. The transition loss could be further reduced by laterally offsetting the straight
section to achieve better mode matching between the straight and bending sections [23]. We have also obtained the relationship between the intrinsic $Q$ of an MRR and the bending radius mediating by the pure bending loss. It has shown that the intrinsic $Q$ is as high as $10^4$ even if one chooses an ultrasharp bend with $R \sim 1 \mu m$.

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The Moore’s Law for photonic integrated circuits

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Received Oct. 10, 2006; revision accepted Oct. 15, 2006

Abstract: We formulate a “Moore’s law” for photonic integrated circuits (PICs) and their spatial integration density using two methods. One is decomposing the integrated photonics devices of diverse types into equivalent basic elements, which makes a comparison with the generic elements of electronic integrated circuits more meaningful. The other is making a complex component equivalent to a series of basic elements of the same functionality, which is used to calculate the integration density for functional components realized with different structures. The results serve as a benchmark of the evolution of PICs and we can conclude that the density of integration measured in this way roughly increases by a factor of 2 per year. The prospects for a continued increase of spatial integration density are discussed.

Key words: Moore’s Law, Photonic integrated circuit (PIC), Photonic lightwave circuit (PLC), Photonic integration density, Photonic filters, Photonic multiplexing

INTRODUCTION

Photonic circuits are currently many orders of magnitude larger in physical dimensions than their electronic counterparts. Whereas FET type transistors have lengths on the order of 50 nm, passive optical devices, even those based on photonic crystals, have sizes on the order the wavelength, 1 μm for customary telecom applications. For active devices the sizes are even larger, at least in length, essentially depending on the matrix element of the interaction in question. Regarding the packing density determining transversal integration, the field extensions are on the order of the wavelength, when dielectrics are used, in contrast to electronics, where the metallic conductors give much better confinement. In addition, electronics features discrete devices with dimensions much smaller than the wavelengths involved, something so far missing in photonics.

In this paper, we formulate a photonics version of famed Moore’s Law (Moore, 1965), a law that has turned out to be a formidable prediction of the future, or maybe has formed the future. We point out the differences that have to be taken into account. As an example we can take an 8×8 arrayed waveguide grating (AWG), which in view of its functionality cannot reasonably be regarded as one single element. Difficulties of this nature do not appear in integrated electronics. Some comments on ultimate limits of photonics integration are therefore given.

MOORE’S LAW FOR PHOTONICS, FORMULATED IN TERMS OF INTEGRATION DENSITY

Moore’s Law concerns electronic integration density and its evolution (exponential progress) in time. The ultimate limit here is power dissipation, because using irreversible entropy lowering devices such as NAND gates will, according to basic ther-
modynamics, always come with heat generation. Only a certain amount of this heat can practically be removed from the chip. Here the exponential progress in the electronic integration density can be attributed to advances in lithography, design and technology in general.

Before achieving a Moore’s Law for photonic integrated circuits (PICs), some remarks on basic differences are in place:

(1) The Moore’s Law for electronic ICs pertains to circuits with generic elements (transistors, resistors, capacitors), some fraction of them are active in the sense that they dissipate power, as noted above. These elements are fabricated by standard processes, applicable to all elements, in one material, silicon, with its natural passivating oxide.

(2) The Moore’s Law for photonics will have to take into account the fact that no generic elements like in electronics exist. On the contrary, the elements are different and employ widely different fabrication processes, and the materials are different too (III-V semiconductors, silicon, ferroelectrics, polymers, etc).

(3) There is no or small power dissipation in a passive case (such as AWGs, switch arrays in ferroelectrics ...) but “high” power dissipation for active devices (lasers, optical amplifiers ...).

We take two approaches to deal with the problem as follows.

Method one

The first method is to transform more complex PICs to “equivalent elements”, as described below, for a reasonably meaningful comparison. Although this is not an exact analogy to electronics, and in a sense it mixes up true integration density in terms of e.g. waveguides per mm, and functionality; and in addition it does not weigh in performance. We feel that it is, in view of the above issues, a reasonable approach. The alternative would be to treat for example an entire 64×64 AWG as one element. Clearly it is not adequate too. Thus, for PLCs, we define the generic elements as:

For passive and non-power-dissipating devices:
(1) 1×2 couplers;
(2) Directional couplers, crossing waveguide couplers;
(3) Filters, including resonators (Bragg filters, photonic crystals ...);
(4) Modulators (electrooptic, reverse biased semiconductor modulators).

Here, in the case of modulators, the power is dissipated in the driving circuitry.

For active devices:
(1) Lasers;
(2) Amplifiers;
(3) Forward biased semiconductor devices;
(4) Detectors (border case).

As an example, a Mach-Zehnder interferometer is equal to two elements (couplers). A quarter wave shifted DFB laser would be two elements. We proceed to an \( N_1 \times N_2 \) AWG (Fig.1a), with \( N \) connecting waveguides and calculate the equivalent number of elements \( N_{eq} \). We construct the equivalent number of 1×2 couplers (Fig.1b), and arrive at the total number of \( N_{eq}=N_1(N-1)+N_2(N-1) \). The formula used for this is:

\[
N_{eq} = \sum_{i=0}^{N_1} 2^i + \sum_{i=0}^{N_2} 2^i .
\]

In the same way we can treat other devices. This is admittedly a rough and somewhat arbitrary method, since it does not consider any difference in e.g. processing for a laser and a dielectric 1×2 coupler. However, it will still give an idea of complexity.
Method two

The first method can be used to treat components such as star couplers and arrayed waveguide gratings. However, it may not be optimal in calculating the integration density for functional components realized with different structures. For example, we consider an $N_1 \times N_2$ (de)multiplexer, which can be realized by either an $N_1 \times N_2$ array of micro-ring resonators (MRRs) or an $N_1 \times N_2$ AWG. According to the first method, an $N_1 \times N_2$ array of MRRs give $N_{eq(MRR)} = 3N_1 \times N_2$ elements since each MRR is equivalent to 3 elements (i.e., two couplers and one ring). With Method One, an $N_1 \times N_2$ AWG demultiplexer gives $N_{eq} = N_1(N-1) + N_2(N-1)$, which is much larger than the equivalent number $N_{eq(MRR)}$ for an array of MRRs since $N$ is usually much larger than $N_{1,2}$. In this way, an $N_1 \times N_2$ AWG may have much higher integration density as compared with an $N_1 \times N_2$ array of MRRs if the occupied area is identical. However, an $N_1 \times N_2$ AWG and an $N_1 \times N_2$ array of MRRs function are the same actually. It is more reasonable to make them equivalent to the same number of basic elements. Therefore, we propose the second method as a complementary algorithm for the calculation of the integration density.

In Method Two, we make a complex component equivalent to a series of basic functional elements. Every type of functional component has a corresponding basic functional element. In this way, two components with the same functionality would have the same equivalent total numbers of basic elements. Then the integration density is determined by their occupied area. For example, for (de)multiplexer, the basic element is a pass-band filter for one wavelength, e.g., a four-port MRR. Thus, an $N_1 \times N_2$ AWG is equivalent to an $N_1 \times N_2$ array of basic filters.

The main difference between the two methods is choosing different basic elements. For Method One, a 1×2splitters etc. are the basic elements. For Method Two, different basic functional elements are used for different kinds of functional components. We calculated the integration density of some typical PIC devices published from 1985 to present by using these two methods (Granestrand et al., 1986; Wisely, 1991; Gustavsson et al., 1992; Trinh et al., 1997; Menezo et al., 1999; Bissessur et al., 1995; 1996; Sasaki et al., 2005; Dai et al., 2006) as examples, and selected the best results according to our Method One, which in a sense overemphasizes the data for AWGs. It can be seen that the increase in density actually outpaces the Moore’s Law prediction, since we have very roughly a factor of 2 per year. Thus, integration density has increased dramatically, but in total number of elements, not much progress is shown over and above (Granestrand et al., 1986) results in nearly 20-years old vintage.

 RESULTS AND DISCUSSIONS

In Fig.2 we show the evolution in integration density for photonics (rather than total number of elements). We have taken references (Granestrand et al., 1986; Wisely, 1991; Gustavsson et al., 1992; Trinh et al., 1997; Menezo et al., 1999; Bissessur et al., 1996; Sasaki et al., 2005; Dai et al., 2006) as examples, and selected the best results according to our Method One, which in a sense overemphasizes the data for AWGs. It can be seen that the increase in density actually outpaces the Moore’s Law prediction, since we have very roughly a factor of 2 per year. Thus, integration density has increased dramatically, but in total number of elements, not much progress is shown over and above (Granestrand et al., 1986) results in nearly 20-years old vintage.

Fig.2 The Moore’s Law in PLC obtained by Method One (Granestrand et al., 1986; Wisely, 1991; Gustavsson et al., 1992; Trinh et al., 1997; Menezo et al., 1999; Bissessur et al., 1996; Sasaki et al., 2005; Dai et al., 2006)

The numbers given in Fig.2 are several orders of magnitude larger than the ones presented in (Smits, 2005), as different methods were used to calculate integration. Also, the rate of increase of integration is
lower in (Smit, 2005) than in the present analysis.

We also summarized the development of the integration density of PLCs by using Method Two considering the integrated filters such as Mech-Zehnder Interferometers, AWGs, and etched diffraction gratings. Fig.3 shows the calculated integration density from 1988 to present (see the discrete dots) and the corresponding linearly fitted line. In Fig.3 the data for the integrated filters based on different materials (such as SiO₂, InP, and Si) are included. From this figure one would see that the integration density almost tripled every year.

In order to observe the influence of the material on the integration density, Fig.4 shows the development in the integration density for the PLC based on InP, SiO₂, and Si, respectively. From the fitted lines in Fig.4a, one can see the integration density of integrated filters based on SiO₂ improves with a factor of 2.5 per year. However, the integration density reached the maximum in 2002. It is difficult to have a higher integration density with SiO₂ for being limited by small refractive index of the SiO₂ buried waveguides.

By using InP waveguides with a strong confinement at the lateral direction, one can have a higher integration density (Fig.4b). Figs.4a and 4b show also that InP can provide higher integration density than SiO₂ does because of a smaller bending radius.

Fig.4c shows the integration density of Si-based integrated filters from 1997 to present. Since the refractive index contrast between Si and SiO₂ (or air) is very large, it is possible to realize some ultracompact PLCs including filters. The integration density of Si-based integrated filters has a very rapid improvement with a factor of 5.5 per year in the past several years (Fig.4c). This is due to the use of Si nanowire waveguides.

An AWG (de)multiplexer is a typical integrated
The Moore’s Law for the development in the integration density of AWG (de)multiplexers based on different materials (for each year we pick up the best result) (Fig. 5) shows an improvement with a factor of 2 per year.

In general, the factors that have brought about rather dramatic increase in integration density in photonics are design, lithography and novel materials (going from ferroelectrics via silica to silicon).

PROSPECTS FOR INCREASED INTEGRATION

Structures with feature sizes in sub-wavelength scale, for instance tens of nm for a 1000 nm vacuum wavelength would certainly increase the integration density. Such structures cannot be based on high index contrast dielectric waveguides, such as Si nanowires. The possible alternative is with negative ε materials, such as metals. The simple type of electromagnetic dispersion that found in metal/dielectric waveguide structure provides some challenging prospects for nanophotonics such as waveguide propagation wavelengths in the X-ray region of light in visible wavelengths. This is made possible by huge reduction in group velocity that can be achieved. This behavior is, however, in today’s materials accompanied by (very) high optical losses, but still offers very intriguing avenues towards real integration and nanophotonics.

Here, one could either rely on “TM-1” or plasmon mode that attached to a metal-dielectric interface, or enclose the optical field arbitrarily well within two metal walls, at the expense of large losses (Bozhevikolnyi et al., 2006).

Regarding the power dissipation, which is the limiting factor today in electronics, we make the comment that this will probably severely limit integration density, due to the thermal sensitivity of the devices involved.

CONCLUSION

In this paper, we have summarized in the development of the integration density of PICs. By using two different approaches, we assessed the “Moore’s Law” for PICs. One is based on breaking down integrated photonics devices in diverse types into equivalent basic elements. The other is to make a complex component equivalent to a series of basic elements of the same functionality. The improvement of the integration density of PICs depends on the materials used, on improved lithography as well as advances in modeling during the 20-year period studied. At present, it seems that Si nanowire waveguides can give passive PICs the highest integration density. It appears that novel materials will be demanded to ensure a sustainable development in integration density. Metal-like materials, though with lower optical losses than metals at room temperature, could play such a role.

ACKNOWLEDGEMENT

We thank Jun Song and Yaqoeng Shi for gathering some parts of the data from the literature.

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Analysis of integrated corner mirrors by using a wide-angle beam propagation method

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Received 11 June 2005; received in revised form 28 October 2005; accepted 28 October 2005

Abstract

An integrated corner mirror is analyzed by using a two-dimensional (2D) wide-angle beam propagation method (WA-BPM) combining with an effective index method (EIM). Both the reflection efficiency and the phase variation due to a total internal reflection (TIR) for the TE and TM modes are calculated. A non-perfect fabrication (such as a tilted or displaced mirror) introduces an additional reflection loss and some errors of the phase variation. The additional reflection loss due to a tilted mirror increases rapidly as the tilted angle increases and becomes more sensitive to the tilted angle when the confinement of the waveguide becomes weaker. It is shown that the displacement of a mirror influences the phase variation greatly and the difference of the phase variation between the TE and TM modes is not sensitive to the displacement of the mirror.

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PACS: 42.82.m; 42.79.Gn; 42.82.Et

Keywords: Corner mirror; Reflection; Loss; Phase variation; Wide-angle; Beam propagation method; Polarization; Fabrication error

1. Introduction

It is often desirable to change the propagation direction of a light beam in a photonic integrated circuit (PIC). A standard way to achieve this is to use a bent waveguide. A strongly confined bent waveguide of a small size has been demonstrated [1]. However, the strongly confined waveguide has a very small spot size, which gives a low coupling efficiency to a standard single-mode fiber (SMF). On the other hand, for a weakly confined bent waveguide, a large cross-sectional size is required to make the bending loss low and this is not good for achieving a high integration density.

A more promising way to change the propagation direction is to utilize an integrated turning mirror [2] based on a total internal reflection (TIR). Some compact structures (such as beam splitters) with corner mirrors [3,4] have been demonstrated and shown good performances. Some theoretical and numerical analyses for corner mirrors have been given [5,6]. A beam propagation method (BPM) is a popular numerical method for integrated waveguide devices. A bi-directional BPM has been used to analyze the reflection for a 90° corner mirror [7]. By choosing the propagation direction appropriately, a paraxial BPM has also been used for the simulation of a corner mirror [8]. However, the
paraxial BPM is not appropriate for a waveguide which has a large angle with the TIR interface. In such a case, a wide-angle (WA) BPM is preferred to achieve a reliable simulation.

For some integrated devices such as splitters, the reflection efficiency is the key issue, on which most of the previous analyses focused. However, not much attention has been paid to the phase variation at a TIR. The phase variation becomes very important and should be considered for a phase-sensitive integrated device such as an arrayed-waveguide grating (AWG) demultiplexer [9] or a Mech-Zehnder interferometer (MZI) when the mirror corner is placed in the phase-shift section of the device. In [10], the Snell law is used to calculate the phase variation at a TIR. It is well known that what the Snell law describes is the reflection of a plane wave from a planar interface of infinite size, but not a guided wave. For an ideal mirror, the reflection of a plane wave from a planar interface of TIR only introduces the reflection efficiency but also the phase variation at the TIR. Nevertheless, not much attention has focused on this case of a non-perfect fabrication (such as a displaced mirror, etc.), one should make a correction by considering the optical path length difference introduced by the displacement or tilting of the mirror.

In the present paper, the three-dimensional (3D) structure of a TIR corner mirror associated with rib waveguides is first converted to a two-dimensional (2D) structure by using an effective index method (EIM). A WA-BPM (instead of a paraxial BPM) is then used to analyze the corner mirror with or without fabrication error. Not only the reflection efficiency but also the phase variation at the TIR mirror are calculated.

2. Theory

The waveguide considered in this paper is single-mode. For a multi-mode waveguide, the total internal reflection at the corner mirror will excite the higher order modes and thus a multi-mode interference will occur at the output waveguide. Fig. 1 shows a typical structure of a corner mirror with single-mode input and output waveguides. The cross-section of the input and output rib waveguides is shown by the inset of Fig. 1. We assume that the 3D rib waveguide can be converted to a 2D slab waveguide by using the EIM. The coordinates are shown in Fig. 1 and we choose the propagation direction of the WA-BPM along the z-axis in the following simulation.

2.1. 2D WA-BPM

For a TE (or TM) mode, one has the following Helmholtz Equation for the 2D scalar electric (or magnetic) field \( \Phi(x,z) \) (all the fields are assumed to have the time-harmonic dependence exp\((-j\omega t))\)

\[
\frac{\partial^2 \Phi}{\partial x^2} + \frac{\partial^2 \Phi}{\partial z^2} + \frac{\omega^2}{c^2} n^2(x,z) \Phi = 0. \tag{1}
\]

As in a standard BPM, we express the field in the following form,

\[
\Phi(x,z) = u(x) \exp(jkz), \tag{2}
\]

where \( k = \bar{n} \cdot k_0, \bar{n} \) is the reference refractive index, \( k_0 \) is the wave number in vacuum. The differential equation for \( \Phi(x,z) \) can be rewritten as [11]

\[
\frac{\partial u}{\partial z} = i\bar{k} \left[ \frac{\partial^2}{\partial x^2} + (k_0^2 n^2 - \bar{k}^2) \right]^2. \tag{3}
\]

where the differential operator

\[
P = \frac{1}{\bar{k}} \left[ \frac{\partial^2}{\partial x^2} + (k_0^2 n^2 - \bar{k}^2) \right]. \tag{4}
\]

By using a \((m,l)\) Padé approximation [12], Eq. (3) is approximated as

\[
\frac{\partial u}{\partial z} = i\bar{k} \frac{N_m(P)}{D_l(P)} u, \tag{5}
\]

where \( N_m(P) \) and \( D_l(P) \) are polynomials of the operator \( P \), \( m \) and \( l \) are the highest powers in \( N_m(P) \) and \( D_l(P) \). By solving Eq. (5), one obtains the field distribution \( u(x,z) \) along the propagation direction in a step by step way.

In our BPM simulation, the fundamental modal field of the input waveguide is chosen to be the incident field. In the \( x'z' \) coordinate system (where the \( z' \)-axis is along the axis of the input waveguide, see Fig. 1), the fundamental modal field of the input waveguide can be written as

\[
E(x',z') = E_0(x') \exp(j\beta z'). \tag{6}
\]

where \( E_0(x') \) is the explicit field distribution of the fundamental mode in the \( x' \)-direction and \( \beta \) is the propagation constant. To obtain the incident field distribution in the \( xz \) coordinate system, the following transformation is used

\[
\begin{align*}
x' &= (x - x_0) \sin \theta + z \cos \theta, \\
z' &= -(x - x_0) \cos \theta + z \sin \theta,
\end{align*}
\]
where $\theta$ is the incident angle, $x_0$ is the x coordinate of point $o$ in the $xz$ coordinate system (see Fig. 1). At the initial plane $z = 0$ for the BPM, one has

$$\begin{align*}
x' &= (x - x_0) \sin \theta, \\
z' &= -(x - x_0) \cos \theta.
\end{align*}$$

(7)

Substituting the above formula into Eq. (6), one obtains the following incident field at the initial plane $z = 0$ in the $xoz$ coordinate system

$$u_{in}(x) = E_0[(x - x_0) \sin \theta] \exp[-j\beta \cos \theta(x - x_0)].$$

(8)

### 2.2. Phase variation

When a TIR occurs, the Snell law gives the following phase variations for the TE and TM polarized plane waves, respectively,

$$\delta_{TE} = 2\tan^{-1}\left[\frac{-n_r \sin^2 \theta - n_i^2}{n_i^2 \cos \theta}\right],$$

(9a)

$$\delta_{TM} = 2\tan^{-1}\left[\frac{-n_r \sin^2 \theta - n_i^2}{n_i^2 \cos \theta}\right],$$

(9b)

where $n_r = n_1/n_2$ ($n_1 < n_2$) and $\theta$ is the incident angle. For a waveguide corner mirror, the above formulas are approximate since the incident wave is not a plane wave but a guided wave. For an ideal mirror, the Snell law may give a reliable approximation. For the case of a non-perfect fabrication (such as a displaced mirror, etc.), one should make a correction by considering the optical path length difference introduced by the displacement of the mirror. In the present paper, we use a WA-BPM to obtain the phase variation at the TIR mirror as follows.

Let $\phi_{in}$ denote the phase of the initial field. By using a WA-BPM, we obtain the complex field $u(x,z)$ distribution at the output plane $z = L$ ($L$ is the length of the computation window along the $z$-direction). The phase $\phi_{out}$ of the complex field $u(x,z)$ at the central axes can be calculated very easily by

$$\phi_{out} = \tan^{-1}[\text{imag}(u)/\text{real}(u)],$$

(10)

where $\text{imag}(u)$ and $\text{real}(u)$ represent the imaginary and real parts of the field $u(x,z)$. Since $\Phi(x,z) = u(x,z) \exp(i\kappa z)$, the phase of the field $\Phi(x,z)$ is given by $\phi_{out} + \kappa L$. The phase introduced by the length $L$ is given by $\beta \sin \theta$, where $\beta$ is the propagation constant. Consequently, the phase variation $\delta_{TE, TM}$ (for the TE or TM mode) at the TIR mirror is given by

$$\delta_{TE, TM} = (\phi_{out} + \kappa L - \phi_{in}) - \beta_{TE, TM} L / \sin \theta.$$  

(11)

Here the propagation distance $L$ should be long enough so that the reflection field at the output end is stable. Usually the propagation length is about several hundreds of micrometers.

### 3. Results and discussions

#### 3.1. Comparison of a paraxial BPM and a WA-BPM

The structure is shown in Fig. 1. For the equivalent slab waveguide, we have $N_{eff2} = 3.4008$, $N_{eff1} = 3.3576$ and $w = 3.0 \mu m$ in the example. The wavelength in the vacuum is $\lambda_1 = 1.15 \mu m$. Theoretically one wishes to place the mirror at a plane crossing the intersection of the axes of the input and output waveguides, i.e., $dx_0 = 0$. To give an accurate analysis, the mesh sizes are chosen to be $\Delta x = 0.0025 \mu m$ and $\Delta z = 0.01 \mu m$.

The reflection loss is defined as $L = -10 \log(P_t/P_0)$, where $P_t$ and $P_0$ are incident power in the input waveguide at plane $z = 0$ and the transmission power in the output waveguide at plane $z = L$, respectively. Fig. 2 shows the reflection loss as the incident angle $\theta$ increases. The reflection loss is calculated by using the paraxial BPM and wide angle BPM based on the approximations of Padé $(1,1)$, Padé $(2,2)$ and Padé $(3,3)$, respectively. From this figure, one sees that the paraxial BPM is not reliable for a waveguide when the incident angle is not large enough when the incident angle (from the waveguide) is smaller than $50^\circ$, the difference between the results from the paraxial BPM and the WA-BPM becomes significant. The calculation accuracy is improved when a higher order Padé approximation is applied. Fig. 2 shows that there is only a slight difference between the results obtained by the WA-BPM based on the approximation of Padé $(2,2)$ and Padé $(3,3)$ even when the incident angle approaches $30^\circ$. A 2D finite-difference time-domain (FDTD) method [13], in which there is no approximation other than the finite difference and the result converges to the exact solution as the discretization step size approaches zero, is also used to calculate the reflection loss and the corresponding results are shown by the cross-marks in Fig. 2. From this figure one sees that the results of the WA-BPM agree with the result of the FDTD. This indicates that the WA-BPM is more reliable than the paraxial BPM.
BPM, particularly when the incident angle is not large enough. Thus, in the following numerical simulation we use the WA-BPM based on the approximation of Padé (2,2).

From Fig. 2 one also sees that the reflection loss varies slightly as the incident angle varies from $30^\circ$ to $75^\circ$ when a TIR occurs. A minimal reflection loss is obtained when the incident angle is about $45^\circ$. According to the Snell law, the reflection loss is zero and independent of the incident angle as long as the incident angle is larger than the critical angle (which is about $17^\circ$ in this numerical example) for a TIR interface. However, for a TIR corner mirror, the structure of the input and output waveguides (usually single-mode) changes in the neighborhood of the mirror. Thus, a mode mismatch (along the WA-BPM propagation direction) is introduced and causes a reflection loss. The mode mismatch is larger when the incident angle increases (larger than $45^\circ$), which results in a larger reflection loss.

### 3.2. The reflection loss

For an ideal corner mirror, the loss is very low (which can be neglected when the incident angle is not too large) when a TIR occurs (see Fig. 2). However, for a non-perfectly fabricated corner mirror, an additional reflection loss will appear. In this section, we give a detailed analysis for the effects of a non-perfect fabrication.

#### 3.2.1. A displaced mirror

Usually a double-photomask process is required to fabricate a TIR corner mirror. In a fabrication, it is hard to make a perfect alignment of the two photomasks and thus the mirror may be displaced. The displacement $\Delta x_b$ of the mirror causes a deviation of the propagation direction of the reflected field (near the mirror) from the axis of the output waveguide. Thus, an additional reflection loss is introduced.

Fig. 3 shows the reflection loss for the TE and TM modes as the displacement $\Delta x_b$ varies when $\theta = 45^\circ$ and $60^\circ$ (with $w = 3.0 \, \mu$m or $5.0 \, \mu$m). From this figure, one sees that for a given requirement of the maximal reflection loss, the tolerance for the alignment of the mirror is larger when the waveguide has a larger width. For example, for the cases of $w = 3.0 \, \mu$m and $w = 5.0 \, \mu$m (with $\theta = 45^\circ$) and a maximal reflection loss of $0.1 \, \text{dB}$, the tolerance for the displacement $\Delta x_b$ is about $0.12 \, \mu$m and $0.20 \, \mu$m, respectively. This can be explained as follows. The field propagation in the input waveguide can be regarded as that in the imaged input waveguide (shown by the dashed line in Fig. 4). When $\Delta x_b = 0$, the central axis of the imaged input waveguide coincides with that of the output waveguide. However, when $\Delta x_b \neq 0$, there is a shift of the central axis between the imaged input waveguide and the output waveguide. This introduces a modal mismatching between the reflected field and the fundamental modal field of the output waveguide. The loss due to this displacement can also be estimated by overlapping the imaged field and the fundamental modal field of the output waveguide. Therefore, for the same displacement, the introduced loss is smaller when the modal spot size is larger (corresponding a wider waveguide). Therefore, one should choose a larger width for the input waveguide in order to obtain a larger tolerance for the mirror displacement.

From Fig. 3 one can also see that the mirror displacement has to be controlled more strictly for a larger incident angle. For example, for $\theta = 45^\circ$ and $\theta = 60^\circ$ (with $w = 3.0 \, \mu$m) and a maximal reflection loss of $0.1 \, \text{dB}$, the tolerance for the mirror displacement is about $0.12 \, \mu$m and $0.10 \, \mu$m, respectively. In order to increase the fabrication tolerance of the mirror position, a smaller incident angle is preferred (certainly should also be larger than the critical angle for a TIR).

![Fig. 3. The reflection loss as the mirror displacement $\Delta x_b$ varies.](image)

![Fig. 4. The schematic configuration for the corner mirror with a displacement.](image)
Due to the Goos–Hänchen shift for a TIR, the optimal position for the mirror is not at the plane of \( dx_b = 0 \). One can place the mirror at the optimal position to reduce the reflection loss. From Fig. 3 one sees that the optimal values of the mirror displacement are almost the same for different incident angles. However, the optimal mirror displacements differ for the TE and TM modes. For the TE mode, the optimal value is \( dx_{b,\text{TE}}^{\text{opt}} \approx 0.06 \, \mu m \). But for the TM mode, the optimal value is almost zero (i.e., \( dx_{b,\text{TM}}^{\text{opt}} \approx 0 \)). One can choose the mirror displacement to be the average of the optimal values for the TE and TM modes, i.e., \( dx_b = (dx_{b,\text{TE}}^{\text{opt}} + dx_{b,\text{TM}}^{\text{opt}})/2 \). In this way, the difference in the reflection losses for the TE and TM modes is small and thus the polarization dependent loss will be small.

Usually the Goos–Hänchen shift is very small since the refractive index difference between the core and air is large. Thus, the optimal displacement is also very small (<0.1 \( \mu m \)) and consequently becomes difficult to realize for a standard fabrication process with a limited alignment precision. Some self-aligned fabrication processes [14] have been proposed and the displacement can be controlled precisely. When a self-aligned fabrication process is applied, the optimal design for the position of the mirror becomes practical and the reflection loss due to the displacement of the mirror can be reduced to a very low level.

### 3.2.2. A tilted mirror

Fig. 5 shows the reflection loss for the TE mode as the tilted angle \( \alpha \) of the mirror plane varies when \( \theta = 30^\circ \), \( 45^\circ \) and \( 60^\circ \). The mirror is placed at the optimal position (\( dx_b = 0.03 \, \mu m \)). From this figure one sees that the additional reflection loss due to a tilted angle of the mirror increases rapidly as the tilted angle increases. When the incident angle \( \theta \) increases from \( 30^\circ \) to \( 60^\circ \), the additional reflection loss only changes very slightly. This indicates that the additional reflection loss is insensitive to the incident angle \( \theta \). On the other hand, Fig. 5 indicates that the additional reflection loss is very sensitive to the width of the waveguide. The additional reflection loss for the case of \( w = 5 \, \mu m \) increases more rapidly than that for the case of \( w = 3 \, \mu m \) when the tilted angle \( \alpha > 0.2^\circ \). However, when \( \alpha < 0.2^\circ \), the difference in the reflection losses for the cases of \( w = 3 \, \mu m \) and \( w = 5 \, \mu m \) is small. Thus, if the tilted angle \( \alpha \) of the mirror can be controlled to be smaller than 0.2\(^\circ\) (which should not be difficult to achieve), the waveguide with a larger width is preferable considering the tolerance of the mirror displacement (see Section 3.2.1).

A comparison between the reflection losses for the TE and TM modes is given in Fig. 6, where the incident angle \( \theta = 45^\circ \). From this figure, one sees that the reflection losses due to a tilted mirror for the TE and TM modes are almost the same. In other words, the reflection loss due to a tilted mirror is polarization-insensitive. This is different from the reflection loss due to a displaced mirror (cf. Fig. 3).

### 3.2.3. The dependence of the reflection loss on \( \Delta n \)

When a rib waveguide is converted to a 2D waveguide by using an EIM, the refractive index difference \( \Delta n \) for the core and cladding of the 2D equivalent waveguide can be controlled by adjusting the etching depth of the rib. Obviously, a deeper etching results in a stronger confinement (i.e., a larger \( \Delta n \)). Fig. 7 shows the additional loss due to a mirror with a tilted angle for the cases of \( \Delta n = 0.01 \) and \( \Delta n = 0.043 \). From this figure one sees that the additional loss becomes more sensitive to the tilted angle when the confinement becomes weaker. For a weaker confinement, the spot size is larger. The tilted mirror introduces larger mode mismatch for a waveguide with a larger modal spot size and thus causes a larger additional reflection loss. This trend is the same as shown in Fig. 5, in which the wider waveguide (\( w = 5 \, \mu m \), corresponding to a larger spot size) is influenced greater than the narrower waveguide.
3.3. The phase variation

When a total internal reflection occurs, there is a difference between the phases of the incident and reflected fields at the surface. We calculate the phase variations of the TE and TM modes for an ideal corner mirror (i.e., \( \Delta x_b = 0 \)) by using the WA-BPM simulation and the Snell law (i.e., Eqs. (9a) and (9b)), respectively. The results are shown in Fig. 8 as the incident angle varies when \( w = 3.0 \mu m \).

Strictly speaking, the Snell law is only for the incidence of a plane wave. From this figure one sees that the phase calculated by the Snell law is quite close to that calculated by the WA-BPM. Thus, for an ideal corner mirror, the simple Snell law can be used to estimate roughly the phase variation.

Below we consider the situation when the mirror is not fabricated perfectly. Fig. 9 shows the phase variation (calculated with the WA-BPM) of the TE and TM modes for a tilted mirror as the incident angle \( \theta \) increases. From this figure one sees that a tilted angle of the mirror does not influence much to the phase variations for the TE and TM modes when the tilted angle is not large. When the tilted angle \( \alpha \) is smaller than 1°, the change in the phase variation is smaller than 0.16 rad for any polarization. Usually the tilted angle \( \alpha \) can be controlled to be smaller than 0.2°. Thus, the influence of the tilted angle to the phase variation is very small. In this case, the Snell law can still be used to estimate roughly the phase variation. For a displaced mirror, one should correct the phase variation from Snell law by considering the optical path length difference introduced by the displacement.

Fig. 10(a) shows the phase variation (calculated with the WA-BPM) for a displaced mirror as the incident angle \( \theta \) increases for the TE mode. From this figure one sees that the phase variation is influenced significantly by the displacement. Fig. 10(b) shows a similar result for the TM mode. The phase variation introduced by the displacement of the mirror can also be estimated according to the optical path length difference due to the displacement, i.e., \( \Delta \phi_{TE,TM} = \beta_{TE,TM} \times 2 \Delta x_b \cos \theta \). Therefore, the total phase variation introduced by the displaced mirror is given by \( \delta_{TE,TM} = \Delta \phi_{TE,TM} + \delta_{TE,TM} \), where \( \delta_{TE,TM} \) is calculated by using formulas (9a) and (9b). The results for \( \delta_{TE,TM} \) are shown by the dashed lines in Fig. 10(a) and (b). One sees that the result with the approximate formula agrees well with that from the WA-BPM. From Fig. 10(a) and (b), one sees that the change of the phase variation due to the displacement of the mirror is not small and thus should be considered in the design of a phase sensitive device.

However, when the phase shift section is an array of waveguides (such as in an AWG demultiplexer), the change of the phase variation due to the displacement will cancel each other if the turn angle 2\( \theta \) is chosen to be the same for all the corner mirrors.

Fig. 11 shows the difference \( (\delta_{TE} - \delta_{TM}) \) between the phase variations of the TE and TM modes when the mirror displacement \( \Delta x_b \) increases. From this figure one sees...
Thus, one should consider the difference \( \delta_{\text{TE}} - \delta_{\text{TM}} \) when designing a polarization insensitive device with a corner mirror. From Fig. 11 one also sees that the difference \( \delta_{\text{TE}} - \delta_{\text{TM}} \) for a fixed incident angle decreases only slightly when the displacement \( dx_b \) varies from a minus value to a plus one.

To see more clearly how sensitivity of the difference \( \delta_{\text{TE}} - \delta_{\text{TM}} \) to the displacement for a fixed incident angle, we show in Fig. 12 the standard deviation of the difference \( \delta_{\text{TE}} - \delta_{\text{TM}} \) (where the displacement \( dx_b \) is controlled within 0.2 \( \mu m \)) as the incident angle increases. From this figure one sees that the standard deviation increases when the incident angle increases. To reduce the deviation of the difference \( \delta_{\text{TE}} - \delta_{\text{TM}} \) due to the displacement \( dx_b \), one should choose a small incident angle. If the incident angle is smaller than 55°, the standard deviation is smaller than 0.01 rad. Usually one can choose the incident angle to be 45° for a 90° turn.

3.4. The polarization dependent wavelength of an AWG

For an AWG, since the effective refractive indices \( n_{\text{TE}} \) and \( n_{\text{TM}} \) of the TE and TM modes are different, the central wavelengths become polarization-dependent. The polarization dependent wavelength (PD\( \lambda \)) is defined as the difference of the central wavelength between the TE and TM modes, i.e., \( \text{PD}\lambda = (n_{\text{TE}} - n_{\text{TM}}) \lambda_{\text{TE}} / n_{\text{TE}} \). Though the difference \( \delta_{\text{TE}} - \delta_{\text{TM}} \) is not sensitive to the displacement \( dx_b \) (cf. Fig. 11), one cannot neglect such a small deviation of \( \delta_{\text{TE}} - \delta_{\text{TM}} \) due to the displacement \( dx_b \) for a polarization compensated phase sensitive device such as an AWG demultiplexer. For a polarization compensated AWG demultiplexer (the polarization compensation is done for \( dx_b = 0 \)), the polarization dependent wavelength (PD\( \lambda \)) introduced by the small deviation of \( \delta_{\text{TE}} - \delta_{\text{TM}} \) is calculated by \( \Delta \lambda_{\text{TE,TM}} = \frac{d \delta_{\text{TE}} - \delta_{\text{TM}}}{2n_{\text{TE}} \lambda_{\text{TE}}} \lambda_{\text{TE}} \) (where \( d \delta_{\text{TE}} - \delta_{\text{TM}} \) is the small deviation of \( \delta_{\text{TE}} - \delta_{\text{TM}} \) due to the displacement \( dx_b \), \( m \) is the diffraction order and \( \lambda_{\text{TE}} \) is the central wavelength). According to the above formula for PD\( \lambda \), one can see that \( d \delta_{\text{TE}} - \delta_{\text{TM}} \) should be smaller than 0.00486 rad if a PD\( \lambda \) of...
0.04 nm (which is a typical requirement for a commercial AWG demultiplexer with a channel spacing of 0.8 nm) is required and \( m = 30, \lambda_c = 1550 \text{ nm} \). However, the standard deviation of \( (\delta_{\text{TE}} - \delta_{\text{TM}}) \) for a certain incident angle (e.g., \( \theta = 55^\circ \)) is about 0.01 rad (see Fig. 12), which is about two times larger than 0.00486 rad. In such a situation, one should reduce the displacement \( dx_b \) by improving the fabrication process with e.g. a self-aligned process. For example, when the displacement is smaller than 0.1 \( \mu \text{m} \), the deviation \( d_{\text{TE}} - d_{\text{TM}} \) is smaller than 0.0042 rad for any incident angle ranging from 45° to 50°. Thus, an allowable \( \text{PD}_k (\approx 0.04 \text{ nm}) \) can be achieved.

To obtain a larger tolerance for the displacement \( dx_b \), one should choose a larger \( m \). For example, if \( m = 120 \), the requirement for \( \text{PD}_k (\approx 0.04 \text{ nm}) \) can be satisfied when \( d_{\text{TE}} - d_{\text{TM}} \) is smaller than 0.0194 rad. In this case, the polarization compensation can be easily realized since the deviation \( d_{\text{TE}} - d_{\text{TM}} \) is smaller than 0.0144 rad even if \( dx_b = 0.2 \mu \text{m} \) (when \( \theta < 65^\circ \)). Therefore, when corner mirrors are inserted in a polarization compensated AWG demultiplexer, a large diffraction order \( m \) should be used. However, this will result in a limited free spectral range and consequently the channel number cannot be very large.

4. Conclusion

A 2D WA-BPM has been used to simulate integrated turning mirrors. The 2D WA-BPM provides more reliable simulation results than the paraxial BPM. Not only the reflection efficiency but also the phase variation have been analyzed. The phase variation at a TIR cannot be neglected for a phase sensitive device. We have analyzed the additional reflection loss and phase variation due to a non-perfect fabrication such as a displaced mirror and a tilted mirror. The difference \( (\delta_{\text{TE}} - \delta_{\text{TM}}) \) between the phase variations of TE and TM modes is not sensitive to the displacement of the mirror. However, one can not neglect the small deviation of \( (\delta_{\text{TE}} - \delta_{\text{TM}}) \) due to the displacement \( dx_b \) for a polarization compensated phase sensitive device. To obtain a larger tolerance for the displacement \( dx_b \), one can use a large diffraction order, which, however, results in a limited free spectral range (i.e., a limited channel number). Thus, it is very important to improve the fabrication process (by using e.g. a self-aligned process) in order to reduce the mirror displacement.

References

Deeply Etched SiO$_2$ Ridge Waveguide for Sharp Bends
Daoxin Dai and Yaocheng Shi

Abstract—A deeply etched SiO$_2$ ridge waveguide including the buffer, core, and cladding is presented for realizing sharp bends. The present SiO$_2$ ridge waveguide has a strong confinement at the lateral direction, while it has a weak confinement at the vertical direction. Due to the strong confinement, a sharp bend (with a very small bending radius of about 10 $\mu$m) is obtained for an acceptable bending loss. A detailed analysis of the loss in a bent waveguide is given by using a finite-difference method. In order to reduce the transition loss, a narrow bending section with an optimal lateral offset is used. A low leakage loss is obtained by using wide straight waveguides, and linear tapers are used to connect the wide straight section and narrow bent sections.

Index Terms—Bending, deep etching, ridge waveguide, silicon oxide.

I. INTRODUCTION

IN THE PAST several decades, photonic integrated circuits (PICs) have been developed drastically because of their excellent performances and compact sizes. There are many kinds of optical waveguides based on different materials and structures, such as InP, SiO$_2$, etc. [1]. Among them, the InP wafer (which is usually used for active PICs) is expensive, and the InP-based waveguide usually has a high fiber-coupling loss due to the small size of the waveguide cross section. For passive PICs, the SiO$_2$ buried waveguide is one of the most popular choices because of its outstanding advantages such as low cost, small propagation loss, and good matching to a single-mode fiber (SMF) [2]–[4]. In order to lower the cost and improve performance, it is becoming more and more attractive to integrate more functional components in a single chip. However, since the refractive index contrast $\Delta$ of SiO$_2$ buried waveguides is usually small ($<$ 2.5%), the bending radius has to be at least several millimeters for an acceptable bending loss (e.g., $R_{\text{min}} = 1.5$ mm when $\Delta = 2.5%$ [2]). Furthermore, a relatively large separation ($> 20 \mu$m) between two parallel SiO$_2$ buried waveguides is required to avoid the evanescent coupling between them. This limits its application for achieving large-scale PICs with high integration densities.

Recently, Si nanowire waveguides have been attractive due to the large difference between the refractive indexes of Si and SiO$_2$ (or air). However, the Si nanowire waveguide usually has a large scattering loss (per unit length) due to the roughness of the sidewall [5], and the coupling to fibers is still a challenge. Therefore, in this paper, we focus on how to realize highly integrated PICs with SiO$_2$ waveguides by reducing the bending radius. In order to achieve a small bending radius, Popović et al. have introduced air trenches in SiO$_2$ bending waveguides [6]. In this way, a very small bending radius (about $\sim 10 \mu$m) has been obtained, and the total size of an air trench bend (including the size of the used taper) is about 100 $\mu$m when $\Delta = 0.75%$. However, for such a design, a complex fabrication (including a chemomechanical polishing and double lithography/etchings) is inevitable [7].

In this paper, we present a deeply etched SiO$_2$-based ridge waveguide (which has a similar to the structure of an InP-based ridge waveguide). In comparison with the structure shown in [7], the present waveguide has a similar sharp bend but simpler fabrication processes. The present waveguide includes three layers of SiO$_2$ films, i.e., the buffer, core, and cladding, which can be deposited on a Si wafer in sequence by using the mature technique of plasma-enhanced chemical vapor deposition (PECVD). Since a deep etching by using an inductively-coupled plasma (ICP) etcher is mature [8], it is not difficult to obtain a deeply etched SiO$_2$ ridge waveguide, which has a strong confinement in the lateral direction, while it has a weak confinement in the vertical direction. Due to the strong confinement, a very small bending radius can be obtained for an acceptable bending loss by choosing the waveguide parameters appropriately. In this paper, we give a detailed analysis of the loss in a bent SiO$_2$ ridge waveguide by using the full-vectorial finite-difference method (FV-FDM) [9]. In order to reduce the transition loss, we use a narrow bending section and optimize the lateral offset. On the other hand, we use wide straight waveguides for a low leakage loss and use linear tapers to connect the straight and bent sections with different widths. Finally, we use a three-dimensional beam propagation method (3D-BPM) [10] to simulate the light propagation in the straight and bending sections.

II. STRUCTURE AND FABRICATION PROCESS

Fig. 1(a) and (b) shows the cross sections of a conventional SiO$_2$ buried waveguide and the present deeply etched SiO$_2$ ridge waveguide, respectively. Both (a) and (b) include three layers of SiO$_2$ thin films with different refractive indexes.

During the fabrication of the conventional buried waveguide, the wafer has to be removed from the chamber of the PECVD machine for the next process of ICP etching after the deposition of the buffer and core layers. This may induce some dust during the fabrication of the conventional buried waveguide, the wafer has to be removed from the chamber of the PECVD machine for the next process of ICP etching after the deposition of the buffer and core layers. This may induce some dust
Fig. 1. Cross section of (a) a conventional SiO$_2$ buried waveguide. (b) Present deeply etched SiO$_2$ ridge waveguide.

(or other impurity) on the surface of the core layer, which is avoided for the present waveguide (see the fabrication process shown in Fig. 2). First, the layers of the buffer, core and cladding are deposited in sequence by using the PECVD technique [see Fig. 2(a)]. By controlling the ratio of the gases, one can adjust the refractive indexes of the layers. The depositions for the three layers are not interrupted by any other process, and thus, the wafer stays in the chamber until the three layers are deposited. The cladding layer protects the core from the influence of the dust in the air. After the deposition of SiO$_2$ thin films, the process of lithography is carried out and forms the designed pattern [see Fig. 2(b)]. The next step is a deep-etching process (see Fig. 2), which is a mature technology [8]. Then, the formed SiO$_2$ ridge waveguide has air cladding at both sides and, consequently, a strong confinement (i.e., the refractive index difference $\Delta n \approx 0.5$) in the lateral direction, while it has a weak confinement ($\Delta n < 0.03$) in the vertical direction. Such a confinement is acceptable since a sharp bending radius can be achieved in the $xy$ plane, which is exactly the desirability for a highly integrated PIC. The fundamental mode in a deeply etched ridge waveguide may have a lower effective index than the cladding index due to air cladding [7], [12], which indicates that the leakage to the buffer layer is inevitable. Fortunately, the leakage loss is very small when the etching depth is large enough. As a comparison, a SiO$_2$ waveguide with $\Delta n \approx 0.5$ (such as a SiO$_2$ membrane waveguide surrounded by air) can provide a sharp bend without any leakage to the substrate. However, the mechanical stiffness of an SiO$_2$ membrane waveguide is not good, and it is not easy to fabricate [11].

III. DESIGN AND ANALYSIS

In order to simplify the design of the present waveguide, we assume that the thicknesses $h_{et}$ and $h_{cl}$ are very large (e.g., $h_{et} = h_{cl} = 6 \mu m$) first so that the modal field is mainly determined by the core width $w$, the core height $h_{co}$, and the refractive index contrast $\Delta$. For a small index contrast $\Delta$, a very deep etching (i.e., a high aspect ratio) is needed for a small bending and consequently introduces great challenges for the fabrication [7]. In this paper, we consider a relatively high index contrast $\Delta = 1.5\%$ and the refractive indexes of the buffer/cladding layers $n_{cl} = n_{bf} = 1.46$. According to the single-mode condition at the vertical direction, we choose the core height $h_{co} = 4.0 \mu m$. By using FV-FDM, we calculate the effective refractive indexes $n_{eff}$ and field distributions of the TE-polarized fundamental mode as the bending radius $R$ increases from 10 to 1000 $\mu m$ for different core widths ($w_{1b} = 1.0, 1.5, 2.0, 2.5 \mu m$).

Fig. 3(a) shows the real part of the effective index $n_{eff}$. From this figure, one sees that the effective index of a bending waveguide decreases and approaches to the effective index of
the straight waveguide \((R = \infty)\) with the same core width when the bending radius increases. When the core width decreases, the effective index decreases due to the weaker confinement. If the core width is smaller than a critical width \(w_0\) (in this case \(w_0 = 2.9 \mu m\)), the confinement is not strong enough to include enough power in the core, i.e., a considerable part of power penetrates to the air claddings at both sides. Thus, the effective index becomes smaller than the refractive index \(n_{\text{eff}}\) of the buffer layer. In this case, only leaky modes (instead of guided modes) are supported, and a leakage loss \(L_{\text{lk}}\) to the substrate is produced. Besides the leakage loss (to the substrate), there is a pure bending loss \(L_p\) and transition loss in a bent waveguide. The transition loss is due to the mode mismatching at the junction connecting the straight and bent sections, which can be estimated by using an overlap integral method. For the leakage loss \(L_{\text{lk}}\) and the pure bending loss \(L_p\), both them are related to the imaginary part of the propagation constant (i.e., the effective index). Since they cannot be calculated separately, we define a propagation loss \(L_{\text{prop}} = 20 \times \log(n_i k_0 R \pi /2), \) where \(n_i\) is the imaginary part of effective index \(n_{\text{eff}}\) and \(k_0\) is the wavenumber in a vacuum. In the present case, the defined propagation loss is the sum of the leakage loss \(L_{\text{lk}}\) and the pure bending loss \(L_p\), i.e., \(L_{\text{prop}} = L_p + L_{\text{lk}}\). In the next part, we will give analyses for the propagation loss and the transition loss, respectively.

For a fixed core width, the leakage loss \(L_{\text{lk}}\) increases linearly as the propagation distance increases. Therefore, a 90° bending with a larger bending radius (i.e., a longer propagation distance) has a larger leakage loss. On the other hand, when the bending radius increases, one usually has a smaller pure bending loss. In the considered cases \((w_B = 1.0, 1.5, 2.0, 2.5 \mu m)\), the leakage loss is much larger than the pure bending loss. Therefore, the total propagation loss \(L_{\text{prop}}\) increases as the bending radius increases, as shown in Fig. 3(b). Nevertheless, from this figure, one sees that the propagation loss is very small (<0.0025 dB) when the bending radius ranges from 1000 to 10 \(\mu m\). Even for an ultrasmall bending radius \(R = 10 \mu m\) (which is over 100 times smaller than that of conventional SiO\(_2\) buried waveguides), one can still achieve a very low propagation loss (<0.0005 dB).

We also calculate the transition loss \(L_t\), which is due to the mode mismatching at the junction connecting the straight and bent sections [see Fig. 3(c)]. Here, we consider that the straight and bending sections have coincident central axes. The transition loss \(L_t\) is estimated by using an overlapping integral method [9]. From this figure, one sees that the transition loss increases dramatically as the bending radius decreases. This is explained as follows. For a smaller bending radius, the modal field distribution (so-called whispering gallery mode [13]) in the bending section is quite different from that in the straight waveguide, and the peak shift of the fundamental modal field becomes larger. This makes the mode mismatching more severe and thus introduces a larger transition loss. When the core width decreases, a smaller transition loss is achieved due to smaller mode mismatching [14]. For example, the transition loss is reduced from 1.8 to 0.07 dB when the core width decreases from 2.5 to 1.0 \(\mu m\). A small core width will give a high aspect ratio and thus increases the difficulty of the fabrication. Therefore, it is desirable to have a relatively wide waveguide with a reduced transition loss.

It is well known that the transition loss can be reduced by introducing a lateral offset \(\delta\) between the axes of the straight and bent sections [15]. Here, we consider an ultrasmall bending radius \(R = 10 \mu m\). Fig. 4 shows the transition loss as the offset \(\delta\) varies for different core widths. This figure shows that there is an optimal offset \(\delta_0\) for a minimal transition loss. One should also note that for the case of a large core width, the transition loss is still relatively large even when one choose the optimal offset \(\delta_0\). For example, when \(w_B = 2.5 \mu m\), the optimal value \(\delta_0\) is about 0.6 \(\mu m\), and the corresponding minimal transition loss is about 0.17 dB (certainly, this has been reduced greatly in comparison with the case of \(\delta = 0\)). For a small core width, a very small transition loss can be obtained when \(\delta = \delta_0\). For example, when we choose \(w_B = 1.5 \mu m\), the transition loss is about 0.04 dB.

From the analysis above, one sees that the bending radius can be as small as 10 \(\mu m\) for an acceptable bending loss.
etching depth offset varies for different underetching depths. The depth considerably as the etching depth increases. The parameters for the bent waveguide in our design are given when the depth $h_{cl}$ decreases. We choose a minimal aspect ratio and keep the symmetry of the bending waveguide (with $\delta = 90^\circ$). The transition loss of a 90$^\circ$ bending, even with the optimal lateral offset $\delta_0$, is about 0.03 dB. From this figure, one also sees that the propagation loss is insensitive to the change of etching depth $h_{et}$. When the thickness $h_{cl}$ decreases from 6 to 1 $\mu$m, the loss $L_{prop}$ increases slightly. In order to achieve a minimal aspect ratio and keep the symmetry of the waveguide in the vertical direction, we choose $h_{cl} = 1.0 \mu$m and $h_{et} = 2.0 \mu$m. For such a design, however, the transition loss of the bending, even with the optimal lateral offset $\delta_0$, becomes larger than 0.1 dB, as shown in Fig. 6. In Fig. 6, we show the transition loss of a 90$^\circ$ bending waveguide (with $w_B = 1.5 \mu$m, $h_{cl} = 1.0 \mu$m, and $R = 10 \mu$m) as the lateral offset varies for different underetching depths $h_{et}$. From this figure, one sees that the optimal offset $\delta_0$ (about 0.17 $\mu$m) is insensitive to the change of etching depth $h_{et}$, and the transition loss increases very slightly until the etching depth $h_{et}$ decreases to 3.0 $\mu$m. When $h_{et} < 3.0 \mu$m, the transition loss increases considerably as the etching depth $h_{et}$ decreases. Therefore, the parameters for the bent waveguide in our design are given as follows: $w_B = 1.5 \mu$m, $h_{et} = 3.0 \mu$m, $h_{cl} = 1.0 \mu$m, and $h_{co} = 4.0 \mu$m.

Fig. 7 shows the leakage loss (in decibels per centimeter) of a straight waveguide with $h_{cl} = 1.0 \mu$m as the core width increases for different depths $h_{et} = 2.0, 2.5,$ and $3.0 \mu$m. When the core width increases, more power is confined in the core layer, and thus, a larger effective index is achieved. Therefore, the field in the buffer layer decays more rapidly, and consequently, the leakage loss becomes smaller, as shown in Fig. 7. When $h_{et} = 30 \mu$m, the core width should be larger than 3.5 $\mu$m for a low leakage loss (about 0.01 dB/cm). Therefore, the core with for the straight waveguide in our design is chosen as $w_B = 3.5 \mu$m. The other parameters are the same as those of the bending waveguides (i.e., $h_{et} = 3.0 \mu$m, $h_{cl} = 1.0 \mu$m, and $h_{co} = 4.0 \mu$m). The total etching depth $H = h_{et} + h_{cl} + h_{co} = 8.0 \mu$m. Fig. 8 shows the leakage loss of a straight waveguide as the core height varies when we fix the total etching depth $H = 8.0 \mu$m, i.e., $h_{et} = H - (h_{cl} + h_{co})$. One
sees that leakage loss is not sensitive to the core height, which indicates a good fabrication tolerance.

In our design shown above, the core widths of the straight and bending sections are different (i.e., $w_B = 1.5 \mu m$ and $w_S = 3.5 \mu m$). Therefore, we introduce tapers to connect them, as shown in Fig. 9. The taper should be long enough to make it adiabatic. Here, we choose the taper length $L_{tp} = 40 \mu m$ and use a 3D-BPM to simulate the light propagation in the designed taper. For the 3D-BPM simulation, the grid size $\Delta x = 0.01 \mu m$, $\Delta y = 0.05 \mu m$, and $\Delta z = 0.05 \mu m$. Fig. 10(a)–(c) shows the field distributions at the planes of $y = 0$, $z = 0$, and $z = L_{tp}$, respectively. From this figure, one sees that the designed taper can transform the modal field successfully, and the excess loss is very low. The total size of the sharp bends ($R \approx 10 \mu m$) with the used taper is about 50 $\mu m$.

For the simulation of light propagation in the sharp bend with $R = 10 \mu m$, we use a 3D-BPM in a cylindrical coordinate system, and the output field from the taper [shown in Fig. 10(c)] is used as the initial field for the 3D-BPM simulation. Fig. 11(a) shows the field distribution at plane $y = 0$ in the bent section ($R = 10 \mu m$) for the case without any offset (i.e., $\delta = 0$). As mentioned above, there is a mode mismatching between the straight and bent sections due to the peak-shift of the modal field in a sharp bend (e.g., $R = 10 \mu m$ in our case). This mode mismatch not only introduces a transition loss but also excites some higher order modes in the bent section. Therefore, an oscillated field distribution is formed due to the interference of the excited multimodes, as shown in Fig. 11(a). When an optimal offset is introduced, more power in the taper is coupled to the fundamental mode of the bent section. Therefore, the transition loss and the excitation of higher order modes are reduced. In this case, the oscillation of the field is almost eliminated, as shown in Fig. 11(b), where the optimal offset $\delta_0 = 0.17 \mu m$. This BPM simulation shows that the present optimized deeply etched SiO$_2$ ridge waveguide can realize a sharp bend ($R = 10 \mu m$) with an acceptable total loss of about 0.1 dB, which includes the propagation loss $L_{prop}(= L_{lk} + L_p = 0.0058 \text{ dB})$, the transition loss $L_t (= 0.06 \text{ dB})$, and the very small excess loss due to the linear tapers.

IV. CONCLUSION

In this paper, we have presented a deeply etched SiO$_2$ ridge waveguide, which has the buffer, core, and cladding. The deep etching introduces a strong confinement at the lateral direction of the present waveguide. This makes it easy to realize a very small bending radius (about 10 $\mu m$) for an acceptable bending loss. The total size of the sharp bends based on the present deeply etched SiO$_2$ ridge waveguide is about 50 $\mu m$ when the size of the used taper is included. We have used an FDM to analyze the loss in a bending waveguide and optimized the width and the later offset of bent sections for a low transition loss. In order to connect wider straight waveguides for a low leakage loss, we have introduced linear tapers between the straight and
Fig. 11. Light propagation in the bent section. (a) $\delta = 0$. (b) $\delta = 0.17 \mu m$. bent sections with different widths. Since the confinement at the vertical direction is weak ($\Delta < 1.5\%$), a small coupling loss to an SMF should be obtained by expanding the modal diameter at the lateral direction with a taper structure. The present deeply etched SiO$_2$ ridge waveguide can be easily used for realizing various PICs, such as an MMI coupler, etc.

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A Minimized SiO$_2$ Waveguide With an Antiresonant Reflecting Structure for Large-Scale Optical Integrations

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Abstract—A minimized SiO$_2$ waveguide with an antiresonant reflecting buffer, a SiO$_2$ core, and an air cladding is presented. The buffer includes multiple periods of antiresonant reflecting structure to lower leakage loss to the substrate. Theoretically speaking, when there are three periods of etch-through antiresonant reflecting structures, one obtains a straight minimized SiO$_2$ waveguide with a low leakage loss ($<$0.01 dB/cm) and a bending radius as small as 15 μm (because of the large index contrast between the core (SiO$_2$) and the air cladding in the lateral direction).

Index Terms—Antiresonant reflecting, bending, deeply etched, leakage loss, SiO$_2$.

I. INTRODUCTION

PLANAR lightwave circuit (PLC) devices are attractive due to their excellent performance, long-term stability, and feasibility for a massive production [1]. Among various developed optical waveguides [1]–[3], SiO$_2$ buried waveguides are very popular for passive PLCs because of their low propagation loss and mature fabrication processes. However, they usually have large bending radii (more than 1000 μm) due to the weak confinement (even with a high index contrast $\Delta = 2.5\%$ [4]). This is too large to realize compact PLC devices used for large-scale optical integration.

Recently, Si nanowire waveguides have been one of the most popular choices to realize ultracompact PLC devices because of the ultrahigh $\Delta$ [3]. However, for the fabrication of such a single-mode waveguide with a submicron core width (e.g., 500 nm), one has to use very expensive irregular lithography technologies such as the E-beam or deep-UV lithography. Furthermore, for the sensing application, which has been one of the most important application areas of PLCs, a smaller core width is preferred to achieve a higher sensitivity to the ambient refractive index, and, consequently, the fabrication becomes more difficult. When one chooses an air cladding and a core with a low refractive index (e.g., SiO$_2$), it is possible to design a single-mode waveguide with a core width more than 1.0 μm for an ultrasmall bending and a high sensitivity while one can fabricate it by using a cheap conventional lithography technique. Therefore, in this letter, we focus on the development of a minimized SiO$_2$ waveguide with an air cladding.

In order to achieve a small bending radius, an air trench has been developed at the bending section of a SiO$_2$ buried waveguide [5]. In this way, an air trench bend with a small total size of about 100 μm (including the size of the used tapers) was obtained. However, a chemomechanical polishing, double lithography processes, and double etchings are needed. Furthermore, a very deep etching is required (which introduces a very high aspect ratio and thus makes the fabrication very difficult). Another way is to use a conventional deeply etched SiO$_2$ ridge waveguide [6]. In this way, the fabrication is much simpler than that shown in [5]; however, it is still not easy to fabricate due to a very large aspect ratio. For example, the etching depth should be larger than 10 μm when the core width $w_{co} = 1 \mu$m and $\Delta = 2.5\%$.

In this letter, we present a minimized SiO$_2$ waveguide, which has a SiO$_2$ core, an air cladding and an etch-through buffer comprising multiple periods of antiresonant reflecting structure. In the past years, antiresonant reflecting optical waveguides (ARROW [7]) have been developed to achieve, e.g., a good confinement in a large core with a low refractive index (e.g., air) [8], a single-mode waveguide with a large core [9]. Here we use an antiresonant reflecting structure to prevent the leakage of light to the substrate. The present SiO$_2$ waveguide has an ultrasmall bending radius ($\sim 15 \mu$m) and a high sensitivity to the ambient refractive index while one can use a cheap conventional lithography technique for the fabrications. In Section II, we use a full-vectorial finite-difference method [10] for the characteristic analysis of the present minimized SiO$_2$ waveguide.

II. DESIGN AND ANALYSIS

Fig. 1 shows the cross section of the present minimized SiO$_2$ waveguide, which includes an air cladding, a SiO$_2$ core, and a buffer with multiple periods of antiresonant reflecting structures. A period of antiresonant reflecting structure includes two layers with different refractive indexes ($n_H, n_L$) and different thicknesses ($h_H, h_L$) given by [7]

$$h_{H(L)} = \frac{\lambda}{4 n_{H(L)}} \left[ 1 - \left( \frac{n_{co}}{n_{H(L)}} \right)^2 + \left( \frac{\lambda}{2 n_{H(L)} h_{eff}} \right)^2 \right]^{-1/2}$$

(1)
where $h_{\text{eff}} = h_{\text{co}} + \zeta (\lambda/2\pi)(n_{\text{co}}^2 - n_{\text{et}}^2)^{-1/2}$ (here $h_{\text{co}}$ is the thickness of the SiO$_2$ core, $n_{\text{co}}$ and $n_{\text{et}}$ are, respectively, the refractive indexes of the core and cladding layers, $\zeta = 1$ and $(n_{\text{co}}/n_{\text{et}})^2$ for TE and TM polarizations, respectively).

In this letter, we consider the TE polarization and choose the wavelength window of 1550 nm as an example of the design. α-Si ($n_H = 3.455$) and SiO$_2$ ($n_L = 1.46$) are used as the materials for the antiresonant reflecting structure. The SiO$_2$ core has a refractive index of $n_{\text{co}} = n_L$ to simplify the fabrication process. These layers of SiO$_2$ and α-Si can be deposited in sequence with a plasma-enhanced chemical vapor deposition technology [3]. Fig. 2 shows the calculated thicknesses ($h_H$ and $h_L$) from (1) as the core thickness $h_{\text{co}}$ increases. From this figure, one sees that the thickness $h_L$ is a bit larger than $h_{\text{co}}/2$ and the α-Si layer is about 0.12 μm thick when 1 μm < $h_{\text{co}}$ < 2 μm.

In order to roughly determine the single-mode condition, a simple way is using an effective index method to make an equivalent slab waveguide and then using the criterion $V < \pi/2$, where $V$ is the normalized frequency of the equivalent slab waveguide. For the analysis of the single-mode operation, we only consider the case with $h_{\text{et}} = h_{\text{co}} + \zeta(h_H + h_L)$ since the etching depth $h_{\text{et}}$ and the period $P$ should be large enough to achieve a low-loss fundamental mode (see Fig. 3). In this case, our numerical calculation has shown that the rough single-mode condition can be given by a fitting function of $w_{\text{co}} < -0.125h_L^2 + 0.69h_L - 1.32h_{\text{co}} + 1.65$. As an example, we design a quasi-single-mode waveguide with $h_{\text{co}} = 1.5$ μm and $w_{\text{co}} = 1.0$ μm. Here the core width is a bit larger than the critical width determined by the previous fitting function to have a small scattering loss. From Fig. 2, one has the corresponding thicknesses $h_L = 0.856$ μm and $h_H = 0.123$ μm. Fig. 3 shows the leakage loss of the present minimized SiO$_2$ waveguide as the etching depth $h_{\text{et}}$ increases. We consider the cases with different total numbers of periods (i.e., $p = 1, 2, 3$). From Fig. 3, one sees that the leakage loss is very large for a small etching depth [e.g., $h_{\text{et}} < h_{\text{co}} + (h_H + h_L)$] and then decreases rapidly as the etching depth increases until $h_{\text{et}} = h_{\text{co}} + p(h_H + h_L)$. When $h_{\text{et}} > h_{\text{co}} + p(h_H + h_L)$, the leakage loss becomes almost unchanged. Therefore, below we choose the design with an etching depth $h_{\text{et}} = h_{\text{co}} + p(h_H + h_L)$. From this figure, one also sees that the leakage loss is reduced greatly as the total period number $p$ increases if one chooses $h_{\text{et}} = h_{\text{co}} + p(h_H + h_L)$. For example, when $p = 3$, the leakage loss is less than 0.01 dB/cm. As a comparison, Fig. 3 also shows the leakage loss of a conventional deeply etched SiO$_2$ ridge waveguide, which has an air upper-cladding, and a 10-μm SiO$_2$ buffer layer with a lower refractive index (Δ = 2.5%) below the SiO$_2$ core ($h_{\text{co}} = 1.5$ μm, $w_{\text{co}} = 1.0$ μm). Our study shows that the etching depth has to be larger than 10 μm for a leakage loss lower than 0.1 dB/cm and thus the large aspect ratio (>10) makes the fabrication difficult.

Fig. 4 shows the leakage loss as the total period number $p$ increases for the case of $w_{\text{co}} = 1.0$ μm and $h_{\text{et}} = h_{\text{co}} + p(h_H + h_L)$ ($p = 1, 2, 3$). From this figure, one sees that the loss decreases exponentially as the total period number $p$ increases. A larger $p$ makes the fabrication more complex. Therefore, one should choose the appropriate period number to achieve a low-loss waveguide with an acceptable fabrication complexity (e.g., $p \leq 3$). The leakage losses for the waveguides with different core thicknesses ($h_{\text{co}} = 1.0, 2.0, 3.0$ μm) are also given in Fig. 4, which shows that a lower loss is achieved by choosing a larger core height. On the other hand, however, a large height may make the waveguide multimode.
Therefore, we choose a tradeoff value for the core height, e.g., \( h_{co} = 1.5 \ \mu m \). With this design, one can have a low leakage loss (<0.01 dB/cm).

A small bending radius is one of the most important factors to realize PLCs with a high integration density as mentioned above. Figs. 5(a) and (b), respectively, show the calculated propagation loss and transition loss for the present minimized SiO\(_2\) waveguide with different core widths (\( w_{co} = 0.8, 1.0, 1.2 \ \mu m \)) when \( h_{co} = 1.5 \ \mu m \). The transition loss is due to the mode mismatching at the junction connecting the straight and bent sections and can be estimated by overlapping their fundamental modes [6]. The propagation loss is defined as \( L_{prop} = 20 \times \log(n_{t}k_{0}R_{\pi}/2) \), where \( n_{t} \) is the imaginary part of effective index \( n_{eff} \), and \( k_{0} \) is the wavenumber in vacuum. Here the propagation loss for a bent waveguide actually includes two nonseparable parts, namely, the leakage loss \( L_{lk} \) and the pure bending loss \( L_{bp} \).

When the core width increases, the pure bending loss \( L_{bp} \) decreases [see Fig. 5(a)]; however, the transition loss \( L_{t} \) increases and becomes dominant [see Fig. 5(b)]. For a requirement of bending loss smaller than 0.1 dB, the bending radius can be as small as 15.0 \( \mu m \), which is over 100 times smaller than that of a conventional SiO\(_2\) buried waveguide. Note that the transition loss can be reduced by introducing an optimal lateral offset [6], [11]. However, our calculation has shown that this reduction is not significant in the present case.

III. Conclusion

In summary, we have presented a minimized SiO\(_2\) waveguide, which has a SiO\(_2\) core, an air cladding, and a buffer with multiple periods of antiresonant reflecting structure. Our simulation results have shown that a very low leakage loss (<0.01 dB/cm) is achieved when three periods of antiresonant reflecting structures are stacked and etched through. The present minimized SiO\(_2\) waveguide can be used not only for an ultrasmall bending but also for a high sensitivity to the ambient refractive index. For an acceptable bending loss (0.1 dB/90\(^\circ\)), the bending radius is as small as 15 \( \mu m \), which is over 100 times smaller than that of a conventional SiO\(_2\) buried waveguide. This facilitates large-scale optical integrations for optical communications and optical sensings. Furthermore, the present single-mode waveguide has a core width about 1 \( \mu m \) and thus can be fabricated by using a cheap conventional lithography technique.

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Low-index-material-based nano-slot waveguide with quasi-Bragg-reflector buffer

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A low-index-material-based nano-slot waveguide based on a quasi-Bragg-reflector buffer is presented. This quasi-Bragg-reflector buffer includes alternating low and high refractive index dielectric layers. The thicknesses of these dielectric layers are chosen optimally by using a genetic algorithm so that the leakage loss of the present optical waveguide is minimised. An SiO₂-based slot-waveguide is designed as an example and the quasi-Bragg-reflector buffer is formed by using several Si/SiO₂ bilayers. The theoretical leakage loss for an SiO₂-based slot-waveguide with three optimised Si/SiO₂ bilayers is about 0.01 dB/mm (at 1550 nm). The modal analysis with a full-vectorial finite-difference method shows that the present slot waveguide has an enhancement of the field distribution in the nano-slot region.

Introduction: To confine guided light tightly in a small size with acceptable loss, recently a nanometre-size slot waveguide has been demonstrated experimentally [1]. Such a slot waveguide has two high-index regions (e.g. Si), between which there is a narrow slot region. This narrow slot usually has a width of about 100 nm (or less) and is filled by a low-index-material (e.g. air or SiO₂) [1]. Because of the continuity of the normal displacement field (product of the permittivity and electric field) at the interface between the low-index slot and the high-index region, one obtains an enhanced electric field intensity in the low-index slot. This effect makes this novel type of optical waveguide very attractive in many applications [2, 3], e.g. modulation, nonlinear effects, sensing etc. In addition, some extended structures, e.g. a horizontal slot waveguide [4], a multiple-slot waveguide [5], etc. have also been developed.

In the previous work, people usually used Si (n = 3.455) and SiO₂ (or air) as the materials in the high-index region and the slot region, respectively. This ultra-high index contrast is suitable for obtaining a large enhancement of field intensity in the slot region. However, in this case, the slot region is only about 100 nm or less at 1550 nm and consequently the fabrication becomes very difficult [6]. Barrios et al. have proposed a slot waveguide based on SiN, which has a refractive index lower than Si so that the slot waveguide has a wider slot region [6]. Consequently, this makes it easier to fill the slot region with some specific materials for nonlinear applications or fluids for sensing applications. Recently, Wiederhecker et al. have demonstrated [7] a photonic-crystal fibre (PCF) based on a similar idea, with a microstructured cladding and an air-slot along the axis of the SiO₂ core.

In this Letter, we propose a planar slot-waveguide based on a low-index material (e.g. SiO₂ or polymer, n ~ 1.57). For such kinds of waveguide, it is not easy to find a suitable material for the buffer-layer, which should have a much lower index than the core in order to prevent leakage to the substrate. To solve this problem, we introduce a Bragg-reflector buffer other than a simple buffer with a single layer of low-index. A Bragg reflector, which consists of alternating low- and high-refractive-index dielectric layers, has been successfully used in the past decade as a mirror, a filter, and a hollow/liquid-core optical waveguide because of its ultra-high reflection efficiency [8]. For the present Bragg reflector, we use alternating pure SiO₂ and Si, which could be formed by using plasma-enhanced chemical vapour deposition (PECVD) technology [9].

In our design, in order to minimise the number of layers as well as the leakage loss, we use a quasi-Bragg reflector instead of a regular Bragg reflector (which is with quarter-wavelength-thick layers [8]). For the quasi-Bragg reflector, the thicknesses of the layers are optimised by using a genetic algorithm (GA).

Structure and design: Fig. 1 shows the cross-section of the present low-index-material-based nano-slot waveguide, which consists of air cladding, a low-index core and a quasi-Bragg-reflector buffer with several Si/SiO₂ bilayers. The thicknesses of the SiO₂/Si thin films can be controlled precisely by slowing down the deposition rate [9]. In a regular Bragg reflector, which comprises quarter-wavelength-thick layers, one has to choose a large bilayer number N (usually N = 5–6 [8]) to enhance the reflection efficiency. This makes the fabrication relatively complex. To simplify the fabrication as much as possible, here we use a quasi-Bragg reflector with only three bilayers (N = 3, i.e. six layers of Si or SiO₂ thin films in total, as shown in Fig. 1) and their thicknesses (h₁₁ , h₁₂, h₁₃, h₂₁, h₂₂, h₂₃, and h₃) are optimised using a GA to achieve a low leakage loss Lᵢ to the substrate. For this GA optimisation, the fitness is defined as the leakage loss Lᵢ (at 1550 nm), which is given by Lᵢ = 20 log₁₀ (exp(βLᵢ)) (dB/mm), where L₀ = 1 mm, β is the imaginary part of the propagation constant β of the fundamental mode and calculated from a full-vectorial finite-difference method (FV-FDM) modal solver [10].

![Fig. 1 Low-index-material-based slot-waveguide with quasi-Bragg-reflector buffer](image.png)

As a design example, we choose SiO₂ as the low-index core material, and the width and height of the SiO₂ core are wᵣ = 0.5 μm and hᵣ = 1.0 μm, respectively. The etching depth is the same as the core height. The refractive indices are nSiO₂ = 1.445, nSi = 3.455, and the central wavelength is λ = 1550 nm. For the case wᵣ = 0.2 μm, one obtains the optimal parameters h₁₁ = 0.1225, h₁₂, h₁₃, h₂₁ = 0.0299, n₁ = 0.4038, 0.1746, 0.2193, 0.2305 μm after about 20 iterations in the GA optimisation and the corresponding leakage loss (at 1550 nm) is very low (~0.0111 dB/mm). Fig. 2a shows the field distribution of the designed slot waveguide with the optimised quasi-Bragg-reflector buffer. From this Figure, it can be seen that the quasi-Bragg buffer successfully prevents the leakage to the substrate. As predicted, there is an enhanced field intensity in the slot region. To see this more clearly, we show the field distribution at the half height of the core in Fig. 2b. From this Figure, one sees that there is an abrupt change of the field distribution across the transition of refractive index and the amplitude at the slot region is about twice that in the SiO₂ core region, which is consistent with the boundary condition for the normal displacement component, i.e. n₁² E₁ = n₂² E₂ (here n₁ and n₂ are the refractive indices of the two materials at the two sides of the interface, and E₁ and E₂ are the electric field amplitudes).

![Fig. 2 Contour field distribution of fundamental mode for TE polarisation, and field distribution at half height of core](image.png)

For the design with wᵣ = 0.5 μm, hᵣ = 1.0 μm and wᵣ = 0.2 μm a Conform field distribution b Field distribution at half height of core

Fig. 3 shows the percentage of the power in the slot region as the slot width wᵣ varies. It can be seen that the power percentage does not change much when the slot width varies. On the other hand, when the slot width increases, the field distribution in the centre will be depressed and the maximal amplitude decreases (see the cases of wᵣ = 0.15 and 0.35 μm shown in the inset of Fig. 3). Therefore, the slot width

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should be small enough to avoid depressing the centre too much. For the present design, \(w_{\text{slot}} = 0.2 \, \mu\text{m}\) is acceptable not only for relatively easy fabrication but also for the enhancement of the electric field in the slot region.

![Diagram](image)

**Fig. 3** Percentage of power in slot region for cases with different slot widths \(w_{\text{slot}}\)

**Conclusions:** We have presented and analysed a low-index-material-based slot-waveguide with a quasi-Bragg-reflector buffer. It has been shown that there is an abrupt change in the electric field distribution across the transition of the refractive index, and the amplitude at the slot region is about twice that in the core region. When the slot width varies, the percentage of power in the slot region does not change much. With the quasi-Bragg-reflector buffer optimised by a GA, the leakage loss at a chosen wavelength is about 0.0111 \(\text{dB/mm}\), which is small enough for most applications such as gas sensing.

**Acknowledgment:** This project was partially supported by research grants of the provincial government of Zhejiang Province (No. 20061343), and the National Science Foundation of China (No. 60607012 and 60688401).

© The Institution of Engineering and Technology 2008
22 May 2008
*Electronics Letters* online no: 20081410
doi: 10.1049/el:20081410

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**References**

Subwavelength Silica-Based Optical Waveguide
With a Multilayered Buffer for Sharp Bending

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Abstract—A subwavelength SiO$_2$-based optical waveguide with an air cladding and a multilayered buffer is presented. This multilayered buffer includes alternating low and high refractive index dielectric layers. The thicknesses of these dielectric layers are chosen optimally by using genetic algorithm so that the theoretical leakage loss of the present optical waveguide is minimized ($<0.001$ dB/mm at the central wavelength, e.g., 1550 nm). The modal analysis with a full-vectorial finite-difference method shows that the present SiO$_2$ optical waveguide has the ability of sharp bending with a very small bending radius ($\sim 10\ \mu m$).

Index Terms—Bending, genetic algorithm, leakage loss, multilayered, SiO$_2$.

I. INTRODUCTION

PHOTONIC integration circuits (PICs) are attractive due to their excellent performances, long-term stability and massive producibility [1]. When a large-scale photonic integration is desirable, it is very important to minimize the sizes of the optical components, for which one of the most important things is to have the ability of sharp bending in an optical waveguide [2]–[4]. By using optical waveguides with high index contrast, it is possible to realize ultrasharp bending and ultrasmall devices. For example, the recently developed Si nanowire waveguide has an ultrahigh index contrast $\Delta (\sim 2:0)$ and consequently could realize an ultrasmall bending radius ($\sim 2\ \mu m$) [5]–[7]. For such a Si nanowire with a very small cross section (e.g., 500 nm $\times$ 250 nm), however, the fabrication is not easy since one usually has to use the expensive E-beam or deep UV lithography process [6].

On the other hand, some low-index materials (such as SiO$_2$, polymer) are very attractive for optical waveguides due to their mature and cheap fabrication processes. How to realize small low-index-cored optical waveguides for sharp bending is an interesting issue [2], [3]. Recently, much attention has been paid on air-cladded SiO$_2$ nanofibers [8]. However, SiO$_2$ nanofibers are not suitable for the realization of optical integrations. In this paper, we focus on planar SiO$_2$ optical waveguides with an air cladding. For the SiO$_2$-on-Si system, one usually uses pure SiO$_2$ and Ge-doped SiO$_2$ as the buffer and the core, respectively [2]. In a conventional deeply etched SiO$_2$ ridge waveguide (similar to InP deep-ridge waveguide) [2], [3], the air cladding introduces a very high index contrast $\Delta$ in the horizontal direction; however, the index contrast $\Delta$ between the buffer layer (pure SiO$_2$) and the core layer (Ge-doped SiO$_2$) at the vertical direction is usually small ($\sim 1\%$ [1]). Therefore, a very deep etching (i.e., very large aspect ratio) is unavoidable in order to achieve a low leakage loss and small bending radius. We also presented another kind of small SiO$_2$ optical waveguide with an antiresonant reflecting buffer [4], which has an aspect ratio of about 3:1 and greatly alleviates the critical requirement of deep etching in comparison with the conventional deeply etched SiO$_2$ ridge waveguide. However, one has to deposit six layers of thin films for that antiresonant reflecting buffer.

In this paper, we present a small air-cladded SiO$_2$ optical waveguide with multilayered buffer. Bragg reflector is a dielectric multilayer stack formed by alternating deposition of low-index material and high-index material and has been successfully used as mirrors and filters because of its ultrahigh reflectivity efficiency in the past decade [9]. It was also used to realize hollow or liquid-cored optical waveguides [10], [11]. For a regular Bragg reflector, quarter-wavelength-thick layers are usually used [9]–[11]. In our case, in order to minimize the layer number as well as a low leakage loss to the substrate, we use a multilayered buffer consisting of only four layers (i.e., two bilayers) with different thicknesses. These thicknesses are chosen optimally with genetic algorithm (GA), which has been used for the optimal design of photonic integrated devices previously [12]. In this paper, we use pure SiO$_2$ and Si as the low- and high-index materials, respectively, which are formed by using plasma-enhanced chemical vapor deposition (PECVD) technology [7]. Here the pure SiO$_2$ is used to avoid Ge-doping. With an optimized multilayered buffer, we obtain a low-loss small SiO$_2$ optical waveguide with the ability of sharp bending ($\sim 10\ \mu m$) and no deep etching is needed. Full-vectorial finite-difference method (FV-FDM) [12] is used for the mode calculation of the present SiO$_2$ optical waveguide.

II. STRUCTURE AND OPTIMAL DESIGN

Fig. 1 shows the cross section of the present subwavelength SiO$_2$ waveguide, which includes an air cladding, a SiO$_2$ core, and a multilayered buffer (with two bilayers consisting of Si and SiO$_2$ thin films). The refractive indices $n_{SiO_2} = 1.445$, $n_Si = 3.455$, and the central wavelength $\lambda = 1550\ \mu m$ and TE polarization is consider in this paper. The width and height of the SiO$_2$ core are chosen as $w_{SiO_2} = 1\ \mu m$ and $h_{SiO_2} = 1.5\ \mu m$ to be single mode and the etching depth is the same as the core.
height to avoid a deep etching. The thin layers of SiO\textsubscript{2} and Si are formed by using the PECVD technology and their thicknesses could be controlled precisely by slowing down the deposition rate [7]. For a regular Bragg reflector, one usually uses quarter-wavelength-thick layers, e.g., the thicknesses of Si and SiO\textsubscript{2} layers are about \( h_{\text{Si}} = 112.2\) nm and \( h_{\text{SiO}_2} = 268.2\) nm (@1550 nm), respectively. It is well known that the reflection efficiency could be enhanced by increasing the bilayer number \( N \) (usually \( N = 5-6\) [9]–[11]), however, which also increases the complexity of fabrication.

In order to simplify the fabrication as much as possible, less bilayer is preferred. Here, we use only two bilayers (\( N = 2\), i.e., four layers of thin films in total, as shown in Fig. 1), which is much less than that for conventional Bragg reflectors (usually \( N = 5-6\) [9]–[11]). The thicknesses \( (h_{\text{H1}}, h_{\text{L1}}, h_{\text{H2}}, \text{and} h_{\text{L2}}) \) of all these layers are optimized with GA optimization to have a low leakage loss \( L_{\text{lk}} \). For this GA optimization, the search ranges for the thicknesses of the high-index layers \( (h_{\text{H1}} \text{ and} h_{\text{H2}}) \) and the low-index layers \( (h_{\text{L1}}, \text{and} h_{\text{L2}}) \) are chosen to be [80 200] (nm), and [200 450] (nm), respectively. Then each thickness \( (h_{\text{H1}}, h_{\text{L1}}, h_{\text{H2}}, \text{or} h_{\text{L2}}) \) is transformed to one binary code with 10 bits as the genes and one obtains four 10-bit binary codes corresponding to these four thicknesses. Then these four 10-bit binary codes are combined to form a chromosome with 40-bit in total. In this case, the precision for the optimization of the thicknesses is about 0.1%, which is related with the bit number \( n \) \((n = 10)\) here of the binary code for each variable. The fitness for the GA optimization is defined as the leakage loss \( L_{\text{lk}} \) at the central wavelength 1550 nm, which is given by \( L_{\text{lk}} = -20 \log[\exp(-\beta L_0)] \) (dB/mm), where \( L_0 = 1\) mm, \( \beta \) is the imaginary part of the propagation constant \( \beta \) of the fundamental mode and calculated from an FV-FDM modal solver. The population number for the GA optimization is 60 for every generation. Here a one-point crossover is used (i.e., the crossover point is chosen randomly for every pair of parents) and the probability for the crossover is 0.5. For GA, mutation (i.e., a small percentage of the genes is changed to the opposite values, e.g., 1 to 0, or 0 to 1) is necessary to have a global searching and to avoid being trapped by a local optimization in the process of GA. We choose the probability of mutation to about 0.02. For the iteration of GA, the initial population is generated randomly first.

The calculated average value and the minimal value of the leakage loss of the population at different generations are shown by the circles (\( \circ \)) and the diamonds (\( \Diamond \)) in Fig. 2(a).

From this figure, one sees the average leakage loss decreases as the generation increases. For the minimal leakage loss, there are some oscillations and only several generations are needed to achieve a set of optimal thicknesses \( (h_{\text{H1}}, h_{\text{L1}}, h_{\text{H2}}, \text{and} h_{\text{L2}}) \) for a very low leakage loss. For example, at the third generation, the minimal low loss (@1550 nm) is only about \( 5.4 \times 10^{-5}\) dB/mm and the corresponding parameters of thicknesses are \( (h_{\text{L1}}, h_{\text{H1}}, h_{\text{H2}}, \text{and} h_{\text{L2}}) = (0.4241, 0.1748, 0.4230, \text{and} 0.1790) \) nm. Even though the layer thicknesses do not satisfy the quarter-wave condition for Bragg grating, such a multilayered structure could still provide a very high reflection, which could be estimated by using a transferred matrix method (TMM) calculation for multilayered thin films. Fig. 3 shows that the field distribution for the optical waveguide with this optimal thicknesses. From this figure, one sees that the multilayer buffer prevent the leakage to the non-covered areas.
substrate successfully and the light is well confined in the SiO₂ core.

For the evolution with more generations, the value of the minimal leakage loss changes but is no more than 0.001 dB/mm. We also give the parameters (h₁₁, h₁₂, h₂₁, and h₂₂) corresponding to the minimal leakage loss at all generations in Fig. 2(b). From this figure, one sees the parameters at different generations do not change much and vary almost around two groups of parameters (h₁₁, h₁₂, h₂₁, and h₂₂) = (0.42, 0.17, 0.43, and 0.17) μm and (0.42, 0.09, 0.43, and 0.17) μm. The main difference between these two groups is the thickness h₁₂. From each of these two groups, we choose the optimal parameters with the minimal loss, i.e., (0.4241, 0.1748, 0.4230, and 0.1790) at the third generation and (0.4234, 0.0945, 0.4312, and 0.1781) at the 58th generation, respectively. Their corresponding leakage losses (@1550 nm) are 5.4 × 10⁻⁵ and 1.52 × 10⁻⁵ dB/mm, respectively. Even though both of them have very low loss, their wavelength dependencies differ very much.

Fig. 4 shows the wavelength dependences of the leakage loss of these two designs (at the third generation and the 58th generation, respectively). From this figure, one sees that they both have two special wavelengths (λ₁ and λ₂) corresponding to locally minimal losses and there is a local maximum of leakage loss Lₘₐₓ between λ₁ and λ₂. When choosing these two groups of parameters, the wavelength spans [λ₁, λ₂] and the local maximum of losses Lₘₐₓ are different, which introduces different bandwidths. When choosing the optimal parameters at the third generation, i.e., (0.4241, 0.1748, 0.4230, and 0.1790) μm, the local maximum of loss Lₘₐₓ is lower than 0.1 dB/mm and consequently the 0.1 dB-bandwidth is as large as 120 nm (ranging from 1450 to 1570 nm and covering the S-band and C-band of optical communications), which is much larger than the case with the parameters at the 58th generation (which gives a 0.1 dB-bandwidth of less than 25 nm). On the other hand, if lower loss is required, the bandwidth will decrease greatly. For example, the bandwidth becomes less than 30 nm for the requirement of Lₐ < 0.05 dB/mm even when choosing the parameters at the third generation.

If a wide bandwidth is desirable, one can choose the fitness for the GA optimization appropriately. For example, by using the average of the leakage losses at 1530 and 1570 nm as the fitness, we obtain a broadened bandwidth of about 66 nm (for Lₐ < 0.05 dB/mm) (as shown in Fig. 5). The corresponding optimal thicknesses are (h₁₁, h₁₂, h₂₁, and h₂₂) = (0.4036, 0.1543, 0.4133, and 0.2025) μm. With such a design, even when Lₐ < 0.02 dB/mm is required, the bandwidth is still relatively large (about 49 nm, from 1.523 to 1.572 μm, covering the C-band).

As a comparison, we also calculate the leakage loss for the GA-optimized design with the same core size (w₀₂ = 1.0 μm, h₀₂ = 1.5 μm) but different bilayer number N. The calculated leakage loss Lₐ (@1550 nm) as the bilayer number N increases is shown in Fig. 6. When N = 1 and 3, the calculated leakage losses at 1550 nm for the design with the optimal thicknesses are about 10.7 and 2.97 × 10⁻⁵ dB/mm, respectively.

Therefore, for the present case (w₀₂ = 1 μm and h₀₂ = 1.5 μm), two bilayers are needed and are enough to achieve a low leakage loss. When a smaller cross-section is desirable, one should increase the bilayer number N to have a low leakage loss. For example, when one chooses w₀₂ = 0.8 μm and h₀₂ = 1.2 μm, three bilayers (N = 3) are needed and the leakage loss at 1550 nm is about 0.000032 dB/mm for the design with the optimal parameters (h₁₂, h₁₂, h₂₁, h₂₂, h₁₁, and h₁₂) = (0.4446, 0.1379, 0.4331, 0.1433, 0.4488, and 0.2098) μm.

As what we mentioned above, a very low-loss optical waveguide at 1550 nm could be achieved when one chooses the optimal thicknesses. However, due to the fabrication errors, the performance of the optimally designed optical waveguide will degrade. In the following part,
we consider the design with \((h_{H1}, h_{H2}, h_{L1}, h_{L2}) = (0.4241, 0.1748, 0.4230, 0.3100, 1.7900) \mu m\) and give an analysis for the fabrication tolerances.

First, we consider the case when the thicknesses of the four layers deviate from their designed values. In this case, the reflectivity of the multilayered buffer decreases and consequently the leakage loss of the subwavelength optical waveguide will increase. The fabrication error \(\Delta H_i\) of thickness is random while could be controlled to be smaller than a certain value \(\Delta H\), which depends on the fabrication process (e.g., the deposition rate). The fabrication error for the \(i\)th layer is given by \(\Delta H_i = \zeta_i \Delta H\), where \(\zeta_i\) is a random (0 \(\leq \zeta_i \leq 1\)). The thicknesses are then given by \((h_{H1} + \zeta_1 \Delta H, h_{H2} + \zeta_2 \Delta H, h_{L1} + \zeta_3 \Delta H, h_{L2} + \zeta_4 \Delta H)\). Here we consider the case with different \(\Delta H\) \((-10, -9, \ldots, 10)\) nm and calculate the leakage losses with ten groups of randomly chosen values of \((\zeta_1, \zeta_2, \zeta_3, \zeta_4)\). The calculated leakage losses are shown in Fig. 7. From this figure, one sees that the minimal leakage loss locates at \(\Delta H = 0\) (i.e., the idea case) as expected and the leakage loss increases slightly (<0.1 dB/mm) when \(-10\) nm < \(\Delta H < +6\) nm. Such a relatively large tolerance makes the fabrication not difficult. Furthermore, the fabrication error could be minimized by slowing down the deposition rate (e.g., \(\sim 1 \AA/\text{s}\) [14]) and thus one achieves a low-loss subwavelength SiO\(_2\) optical waveguides with tolerable fabrication errors.

In addition to the thicknesses \((h_{H1}, h_{H2}, h_{L1}, h_{L2})\) of all the layers in the buffer, the core height and the core width also play important roles for achieving an optical waveguide with a low leakage loss for the present case.

Fig. 8(a) shows the leakage loss \(L_{\text{lk}}\) when the core height \(h_{co}\) deviates from their design values, respectively. From this figure, when the core height \(h_{co}\) increases from \(h_{co}\), the leakage loss increases slightly. Even when the core height \(h_{co}\) increases to 1.8 \(\mu m\) (with a deviation of 0.3 \(\mu m\)), the leakage loss is still less than 0.1 dB/mm. On the other hand, when the core height \(h_{co}\) decreases from \(h_{co}\), the leakage loss increases more remarkably. When \(h_{co}\) < 1.38 \(\mu m\), the leakage loss becomes larger than 0.1 dB/mm. From this figure, one sees that there is a relatively large fabrication tolerance for the core height. Usually it is not difficult to make the deviation of the core height smaller than several tens of nanometers during the fabrication process.

Fig. 8(b) shows the leakage loss \(L_{\text{lk}}\) for the optimized optical waveguide when the core width \(w_{co}\) deviates from the designed value \((w_{co} = 1.0 \mu m)\). The inset in Fig. 8(b) gives the enlarged view for the leakage loss \(L_{\text{lk}}\) around \(w_{co} = w_{co0}\). From this figure, one sees that the variation of the core width influences the leakage loss significantly. When the core width becomes smaller than its designed value \(w_{co}\), the leakage loss increases considerably. For example, when \(w_{co}\) decreases to 0.95 \(\mu m\), the leakage loss is close to 0.5 dB/mm.

When \(w_{co}\) increases (i.e., \(w_{co} > w_{co0}\)), one obtains another local minimum of leakage loss \((L_{\text{lk}} \sim 0.05 \text{ dB/mm})\) at \(w_{co} = w_{co2} \sim 1.16 \mu m\), see the inset which is another special width for the locally minimal loss in addition to \(w_{co0}\). In the range of \(1.0 \mu m < w_{co} < 1.16 \mu m\), there is a local maximum of leakage loss \(L_{\text{max}}\) (about 0.25 dB/mm) @ \(w_{co} = 1.06 \mu m\). If \(L_{\text{lk}} < 0.25 \text{ dB/mm}\) is allowable, the core width \(w_{co}\) should not be out of the range from 0.98 to 1.2 \(\mu m\). When a smaller leakage loss is required, the fabrication tolerance for the core width is not large and consequently one has to control the core width more precisely during the fabrication processes. From Fig. 8(b), one also sees that the leakage loss oscillates notably as the core width increases until \(w_{co} = 4.5 \mu m\). From Fig. 8(b), one has minimal leakage losses when choosing \(w_{co} = 1.8, 2.5,\) and \(3.0 \mu m\). When the core width increases further (i.e., \(w_{co} > 4.5 \mu m\)), the leakage loss becomes almost unchanged and one has \(L_{\text{lk}} \approx 0.5 \text{ dB/mm}\).

Therefore, when it is necessary to use optical waveguides with different core widths on the same substrate, one should choose their core widths carefully to ensure low leakage losses. For example, a multimode interference (MMI) coupler has

![Fig. 7. Leakage loss \(L_{\text{lk}}\) when there is a random fabrication error.](image1)

![Fig. 8. Leakage loss \(L_{\text{lk}}\) when (a) the core width and (b) the core height deviate from their designed values.](image2)
narrow access optical waveguides and a wide MMI section. When the MMI section is relatively small (e.g., $w_{\text{co}} < 4.0 \, \mu m$), one can choose the special core width (e.g., $w_{\text{co}} = 2.5, 3.0 \, \mu m$) to have a minimal leakage loss. For a MMI coupler with large input/output port number, a wider MMI section is needed (e.g., $w_{\text{co}} > 4.0 \, \mu m$) and consequently the leakage loss is about 0.5 dB/mm. Fortunately, the MMI section is usually short (no more than 100 \, \mu m). Therefore, the leakage loss in the MMI section is small enough to be negligible. Therefore, the influence of the core width variation on the leakage loss should not limit the application of the present subwavelength optical waveguide (which is available for various photonic integrated circuits).

Fig. 9(a) and (b) shows the wavelength dependence of the leakage loss when the core height and core width deviate from their designed values, respectively. From Fig. 9(a), one sees that the deviation of the core height influences the wavelength dependence of the leakage loss greatly. When the core height is small (e.g., $h_{\text{co}} = 1.3 \, \mu m < h_{\text{des}}$), one has a U-shape wavelength-dependence which has only one special wavelength ($\lambda_1$) for minimal leakage loss. For example, when $h_{\text{co}} = 1.3 \, \mu m$, one will obtain a minimal leakage loss of about 0.11 dB/mm at $\lambda_1 = 1.505 \, \mu m$ and the bandwidth is relatively small. When the core height increases, the wavelength dependence of the leakage loss becomes W-shaped, which indicates there are two special wavelengths ($\lambda_1, \lambda_2$) for minimal leakage losses [see Fig. 9(a)]. As the core height increases, $\lambda_1$ decreases and $\lambda_2$ increases, which results in a larger span [$\lambda_1 - \lambda_2$]. Therefore, the bandwidth becomes relatively large (e.g., the 0.05 dB-bandwidth is about 65 nm when $h_{\text{co}} = 1.4 \, \mu m$). On the other hand, one should note that the local maximum $L_{\text{max}}$ in the range of $[\lambda_1, \lambda_2]$ increases for a larger $h_{\text{co}}$. Consequently, the bandwidth is limited by the local maximum $L_{\text{max}}$. For example, for the cases of $h_{\text{co}} = 1.5$ and $1.6 \, \mu m$, their local maximum $L_{\text{max}}$ are about 0.096 and 0.135 dB, respectively. Therefore, the 0.1 dB bandwidth decreases significantly when $h_{\text{co}}$ increases from 1.5 to 1.6 \, \mu m. The wavelength dependence of the leakage loss for the case when the core width deviates from the designed value ($w_{\text{co}} = 1.0 \, \mu m$) is shown in Fig. 9(b). From Fig. 9(b), one sees that when the core width increases from 0.9 \, \mu m to 1.2 \, \mu m, the shape of the wavelength dependence changes from a U-shape to a W-shape with one or two special wavelengths for minimal leakage loss, which is similar to the case shown in Fig. 9(a).

From Fig. 9(a) and (b), one sees that the leakage losses at the special wavelengths ($\lambda_1, \lambda_2$) are very low ($<0.01 \, \text{dB/mm}$) for the W-shaped wavelength-dependence of the leakage loss. Therefore, when the core height and the core width deviate from their design values ($h_{\text{co}} = 1.5 \, \mu m, w_{\text{co}} = 1.0 \, \mu m$), one can choose its special wavelengths ($\lambda_1, \lambda_2$) as the operation wavelength for the minimal leakage loss in some applications (whose operation wavelength is allowed to be changed).

In order to realize PICs with a high integration density, a low-loss sharp bending is one of the most important things. Fig. 10 shows the propagation loss $L_{\text{prop}}$ and the transition loss $L_t$ in a 90° bend as the bending radius $R$ varies.
optical communications but also for other applications (such as optical sensing).

III. CONCLUSION

In summary, we have presented and theoretically analyzed a small air-cladded SiO$_2$ optical waveguide. A multilayered buffer, which includes alternate low and high refractive index dielectric layers, has been introduced to reduce the leakage loss to the substrate. The FV-FDM modal solver has been used for the modal analysis of the present small SiO$_2$ optical waveguide. In order to minimize the leakage loss, GA has been used to optimize the thicknesses of these dielectric layers in the Bragg-reflector buffer. With the optimized multilayered buffer with only two bilayers, the leakage loss at a chosen wavelength is as small as $5.4 \times 10^{-5}$ dB/mm for the central wavelength (e.g., 1550 nm). Our numerical simulation has shown that the present SiO$_2$ optical waveguide has the ability of sharp bending with a bending radius of $<10$ mm. For such a sharp bending, it does not need any deep-etching process. We have also investigated the fabrication tolerance of the layers thicknesses and the core size. It has been shown that there is a relatively large fabrication tolerance (e.g., the leakage loss $L_{BR} < 0.1$ dB/mm when $\Delta H < 6$ mm). Since the fabrication error could be minimized by slowing down the deposition rate (e.g., $\sim 1$ Å/s), it is not difficult to achieve low-loss propagation in the present subwavelength SiO$_2$ optical waveguide. In addition, by using the present structure with multilayered buffer, it is also possible to develop a similar small optical waveguide based other low-index materials (e.g., polymers).

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Experimental Demonstration of Deeply-Etched SiO₂ Ridge Optical Waveguides and Devices

Zhen Sheng, Bo Yang, Liu Yang, Jing Hu, Daoxin Dai, Member, IEEE, and Sailing He, Senior Member, IEEE

Abstract—Deeply-etched SiO₂ optical ridge waveguides are fabricated and characterized. A detailed discussion of the fabrication process (especially for the deep etching process) is presented. The measured propagation losses for the fabricated waveguides with different core widths range from 0.33 ∼ 0.81 dB/mm. The loss is mainly caused by the scattering due to the sidewall roughness. The losses in bending sections are also characterized, which show the possibility of realizing a small bending radius (several tens of microns). 1 × N (N = 2, 4, 8) multimode interference couplers based on the deeply-etched SiO₂ ridge waveguide are also fabricated and show fairly good performances.

Index Terms—Bending, deep etching, loss, multimode interference (MMI) coupler, ridge waveguide, SiO₂.

I. INTRODUCTION

In the past several decades, optical waveguide-based planar lightwave circuits (PLCs) have been developed drastically because of their excellent performances. Among various kinds of waveguides with different materials or structures, the SiO₂-on-Si buried waveguides [1] is one of the most popular choices due to their outstanding advantages such as low cost, mature fabrication process, small propagation loss, and good matching to a singlemode fiber (SMF). However, the bending radius of the SiO₂ buried rectangular waveguide is usually very large (several millimeters or centimeters) for an acceptable bending loss because of its low refractive index contrast (e.g., 0.25% [2] ∼ 2.5% [3]), which limits the integration density of PLCs to a fairly low level. In order to achieve ultra-small PLCs, the SOI (silicon-on-insulator) nanowire waveguide [4]-[5] has become very popular recently because of its large index contrast (i.e., strong light confinement). However, there are several challenges for SOI nanowaveguides and devices, e.g., large coupling loss to an SMF, and serious sidewall scattering loss. SOI nanowaveguides can only be applied in the infrared range due to the large absorption coefficient of silicon at the wavelengths smaller than 1.1 μm, which prohibits SOI nanowaveguides from some applications for optical sensing in the visible range. Additionally, the fabrication of SOI nanowaveguides requires electronic beam (E-beam) [4] or deep-ulaviolet (DUV) lithography[5] facilities, which increases the fabrication cost. In the present paper, we fabricate and characterize a deeply-etched SiO₂ ridge waveguide, which can overcome the above-mentioned problems for an SOI waveguide. We also design and fabricate 1 × 2, 1 × 4, and 1 × 8 multimode interference (MMI) couplers to show the usefulness of this new type of optical waveguide.

Fig. 1 shows the cross section of a deeply-etched SiO₂ waveguide [6]. The three SiO₂ layers (buffer, core and cladding) deposited consecutively on the Si substrate are etched through. Due to the strong lateral confinement, the bending radius can be as small as < 100 μm for an acceptable bending loss. The lateral size of this kind of waveguide is moderate (a few micrometers) so that the conventional UV lithography system with a mercury lamp are sufficient to pattern the waveguide. Furthermore, by etching to the substrate, we can avoid the stress induced by the deposited silica layers. Otherwise, an extra oxide layer should be added on the backside of the Si substrate to maintain a flat wafer [7]. Because of the large transmission window of SiO₂, this waveguide can be used in a wide wavelength range from visible to infrared. Apart from the applications in optical communication and interconnects, the deeply-etched SiO₂ waveguide can be conveniently used for sensing applications since its core can be in direct touch with the sample to obtain a high sensitivity. Although the optical modes in the waveguide are intrinsically leaky, the leaky loss can be negligible as long as the etching depth is large enough and the loss may not be so critical in some sensing applications.

II. FABRICATION

The fabrication process is shown in Fig. 2. First, the layers of buffer, core and cladding were deposited in sequence by the plasma-enhanced chemical vapour deposition (PECVD) system [Fig. 2(a)]. The buffer and cladding were made of pure SiO₂, while the core was Ge-doped to increase the refractive index. The refractive indexes of the buffer/cladding and core layers

Manuscript received January 07, 2009; revised March 21, 2009. Current version published December 09, 2009. This project was supported in part by Zhejiang Provincial Natural Science Foundation of China (No. J20081048), the National Science Foundation of China (60688401). The authors are with the Centre for Optical and Electromagnetic Research, State Key Laboratory of Modern Optical Instrumentation, Zhejiang University; Hangzhou 310058, China (e-mail: dxdai@zju.edu.cn).

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Digital Object Identifier 10.1109/JQE.2009.2023610
were measured to be 1.455 and 1.465, respectively, by using a prism coupler. For the present optical waveguide, a deep etching (> 10 μm) is needed and the feature size is relatively small, which means a high aspect ratio. Thus, one should choose an etching mask with a high selectivity to SiO₂, which is very important to achieve a vertical etching profile. In our experiment, we chose Ti/Ni bilayer metal mask (instead of photoresist or silicon) for the SiO₂ etching. And a lift-off process was performed to form the metal mask [see Fig. 2(b) and (c)] and the metal layers were deposited by using a magnetron sputtering process.

For the following SiO₂ etching, we used a dry-etching process with an inductively-coupled plasma (ICP) etching system. In order to realize a highly-qualified deep etching, the process parameters should be optimized. For the ICP etching, one could obtain a higher etching rate with a higher platen RF power and a lower chamber pressure. However, in this case, the physical etching effect becomes stronger and consequently the etching selectivity is reduced [8]. If the metal mask is not thick enough, a slanted sidewall will be formed because the metal mask is etched faster at the edges than at the middle region. On the other hand, when a thick metal mask is desirable, one has to choose a thick photoresist film (in order to successfully strip the metal during the lift-off process), which is not good to have a high resolution for the UV lithography. Furthermore, in this case, the cross section of the formed metal mask is trapezoid-like (i.e., the thickness at the edge is thinner than the middle region), which will introduce a slanted etching profile. After several tests, we made a trade-off and chose a 300-nm-thick metal layer as the etching mask.

For the ICP etching, the process parameters are summarized in Table I. Under such an etching condition, it took about 105 minutes to realize an etching depth of 17 μm. It is possible not to remove the residual metal mask after etching as long as the cladding layer is thick enough to guarantee a low absorption loss of metal. Compared to a conventional SiO₂ buried waveguide, the present deeply-etched SiO₂ waveguide has a simple fabrication process since the conventional one needs a process of deposition-etching-redeposition.

Fig. 3 shows the SEM (scanning electron microscopy) view of the cross section of a fabricated deeply-etched SiO₂ waveguide (with a nominal width of 3 μm). In this figure one can distinguish three SiO₂ layers according to their different gray levels (to see clearly, we mark the interfaces between these layers with dashed lines). The thicknesses of the buffer, core and cladding are about 6.35 μm, 5.99 μm and 3.84 μm, respectively. The overall depth of etching is about 16. μm and the etching profile is overcut with a sidewall angle of 86.4°. Since the cladding layer is thick enough here, the absorption loss caused by the metal mask is negligible (∼ 0.01 dB/mm) for TE mode according to our simulation. For TM mode, the absorption loss due to the metal mask is larger while still much smaller than the sidewall scattering loss (which is the dominant source of the propagation loss). Thus, we did not remove the residual metal mask after etching for a simplified fabrication process. To explore the mode field distribution inside the waveguide, we used a CCD (charge-coupled device) camera to capture the output spot (θλ = 1.55 μm) from the 3 μm-wide waveguide, as shown in the inset of Fig. 3. Due to the limited resolution of the CCD camera, it is not easy to give the accurate size of the spot from Fig. 3. Fortunately, from the CCD-captured picture in Fig. 3,

![Fig. 2. The fabrication process for our deeply-etched SiO₂ waveguide.](image)

<table>
<thead>
<tr>
<th>TABLE I</th>
<th>THE PARAMETERS FOR THE ICP ETCHING PROCESS</th>
</tr>
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<tbody>
<tr>
<td>Coil RF power (W)</td>
<td>800</td>
</tr>
<tr>
<td>Platen RF power (W)</td>
<td>50</td>
</tr>
<tr>
<td>Chamber pressure (mTorr)</td>
<td>3</td>
</tr>
<tr>
<td>Gas flow (sccm)</td>
<td>50 (CHF₃), 6 (CF₃)</td>
</tr>
</tbody>
</table>
one could clearly see that the mode field is well confined and has an elliptical spot. For a comparison, here we use the imaginary-distance beam propagation method (ID-BPM) [9] for the calculation of the mode field of the optical waveguide with the same size and a vertical sidewall (see Fig. 4). One sees that the theoretical mode spot is quite similar with the CCD-captured one (see Fig. 3), which indicates that the slightly slanted sidewall does not influence much the mode distribution.

Small sidewall roughness is very important to obtain a low-loss optical waveguide. Usually it is desirable to measure the sidewall roughness for the estimation of the scattering loss and the evaluation of theetching quality. Some special treatments in combination with an AFM (atomic force microscopy) are needed for the direct and accurate measurement of the sidewall roughness. For example, Y. Matin et al. used a specially prepared high aspect ratio boot-shaped AFM tip mounting in an AFM system [10] and J. H. Jang et al. devised a special staircase pattern to allow AFM tip to access the etched sidewall in the normal direction [11]. Here, we give a simple estimation for the sidewall roughness through an SEM photo for the top view of the fabricated waveguide (see Fig. 5). This figure shows that the waveguide sidewall is relatively rough and the estimated roughness is $100 \sim 200$ nm. This is responsible for the relatively high propagation loss as shown in the following section.

Fig. 3. The SEM view of the cross section of a fabricated deeply-etched SiO$_2$ waveguide (with a typical width of 3 $\mu$m). Inset: the corresponding mode spot (for $\lambda = 1.55$ $\mu$m) at the output end captured by a CCD camera.

Fig. 4. The mode field distribution of a 3-$\mu$m-wide waveguide obtained by ID-BPM. The outline of the waveguide is also indicated with white lines.

III. MEASUREMENT

A. Propagation Loss and Coupling Loss

We have fabricated several straight deeply-etched SiO$_2$ waveguides with different widths and estimated the propagation loss as well as the coupling loss to the fiber by using the cutback method. The measured results are shown in Fig. 6. Then the propagation loss and coupling loss can be extracted and shown in Fig. 7. Here, tapered lens fibers (TLF, mode diameter $= 3 \sim 4$ $\mu$m) were used to couple light into and out of the waveguides. One sees that the propagation loss increases almost linearly when the waveguide width decreases. When the core width $w$ decreases from 4 $\mu$m to 1.8 $\mu$m, the propagation loss increases from 0.33 to 0.81 dB/mm. Since the lateral index contrast is quite high, the propagation loss may be sensitive to the sidewall roughness [12]. Smoother sidewalls can be obtained by optimizing the lithography and etching processes. Leakage to the substrate is another origin of the propagation loss. An effective way to reduce the leakage loss is to increase the index contrast between the core layer and the buffer layer so that the light confinement becomes stronger in the vertical direction. Previous study has shown that the index contrast $\Delta$ can reach as large as 2.5% [3]. Then the thicknesses of both the core and buffer can also be greatly reduced and a shallow etching process can be used. In this way, it is much easier to realize a smooth sidewall, which reduces the scattering loss. The coupling losses between the waveguide and the TLF are around 2 dB/facet and slightly vary with waveguide width $w$. The smallest coupling loss is about 1.5 dB/facet when $w = 3.4$ $\mu$m. This is reasonable considering that the mode diameter of the TLF is $3 \sim 4$ $\mu$m. The coupling loss can be further reduced by polishing the waveguide facet after cleaving, or adjusting the width of the input/output section locally to achieve a better mode match to the fiber used.

B. Bending Loss

In order to determine the bending loss, we have designed and fabricated several sets of S-bend structures. Within each set, all the bending structures have the same bending radius $R$ but different number of 90° bends (see Fig. 8). Here we measured the bending losses for the optical waveguide with a core width of 2.2 $\mu$m as an example for the first experimental demonstration.
In future work, the choice of the waveguide width should be application-oriented. For example, for a wider waveguide, the propagation loss is smaller as shown in the above section, while there is a larger transition loss between the straight waveguide and the bending waveguide [6].

Fig. 9(a) shows the bending loss for a 90° bend for different bending radii $R$. An exponentially fitted curve of the measured data is also shown. The bending loss decays exponentially when the bending radius $R$ increases, as expected. The bending loss includes the substrate leakage loss, the bending-related radiation loss, the transition loss, and the sidewall scattering loss. The first two sources of loss can be estimated by the imaginary part of the effective index of the mode and the simulation results show that they are negligible.

The transition loss occurs at the junction between the sections with different curvature radii due to the mode mismatch. An effective way to reduce the transition loss is to introduce a lateral offset $\lambda$ between the two sections to achieve a better mode match [13]. Fig. 9(b) shows the measured bending loss of $R = 20 \mu m$ when introducing different lateral offsets. A fitted curve for the data is also shown. One sees that the bending loss decreases as the offset increases until a minimal loss is reached. The bending loss can be reduced by over 0.2 dB when an optimal offset (around 0.25 $\mu m$ in this case) is used. We also investigated numerically the wavelength dependency of the transition loss when introducing different offsets, as shown in Fig. 9(c). The transition loss was estimated by using an overlap integral method [14]. One sees that the optimal offsets for the wavelength band considered here (1450 $\sim$ 1650 nm) are all around 0.25 $\mu m$, which agrees well with the measurement results in Fig. 9(b). The minimal transition losses (corresponding to the optimal offset) for all of the wavelengths are almost the same, i.e., $\sim 0.03$ dB. Therefore, it is possible to realize a low-
loss and wideband bending structure. When there is no offset (i.e., $\delta = 0$), the transition loss for a shorter wavelength is larger than that of a longer wavelength. This is because the modal field for a shorter wavelength shifts more outward in the bending waveguide, introducing a larger mode mismatch with the straight waveguide. For a larger bending radius, the optimal offset should be smaller since the mode mismatch becomes smaller. The transition loss can be further reduced by adopting waveguides with smaller widths [6].

The last source of bending loss is the sidewall scattering loss when light propagates in the bending structure. The sidewall scattering loss is an important source of loss. In the bending structure, the optical modal field shifts outward in the bending structure and subsequently enhances the interaction with the rough sidewall. Thus, the sidewall scattering loss is much more serious than that in the straight waveguide. Therefore, it is very important to optimize the fabrication process (especially the ICP etching) as well as the design of the optical waveguide [6] in the future. In this way, as theoretically predicted, one could achieve a low loss ($\leq 0.1$ dB/90°) even for a bending radius of several tens of microns (two orders of magnitude smaller than that for a conventional SiO$_2$ buried waveguide) [6].

C. Polarization Dependency

Due to the structure asymmetry in the transverse and vertical directions, the effective index of the deeply-etched SiO$_2$ ridge waveguide may be polarization-sensitive. Fig. 10 shows the calculated effective indexes ($n_{\text{eff}}(\text{TM})$, $n_{\text{eff}}(\text{TE})$) of TE and TM polarization modes for the present structure ($h_{\text{th}} = 6.35$ $\mu$m, $h_{\text{cd}} = 5.99$ $\mu$m, and $h_{\text{cl}} = 3.84$ $\mu$m). From the figure, one sees the birefringence (defined as the difference of the effective indexes between TM and TE polarizations, i.e., $n_{\text{eff}}(\text{TM}) - n_{\text{eff}}(\text{TE})$) is small especially for the case with a large core width (e.g., $w_{\text{cd}} = 4$ $\mu$m). When the core decreases, the birefringence becomes larger. For example, for a core width as small as 1.5 $\mu$m, the birefringence is about 0.02. By adjusting the layer structure (e.g., optimizing the thickness of each layer), it is possible to further reduce the polarization dependency to a negligible level for most applications (e.g., with a birefringence of $10^{-4} \sim 10^{-5}$). For a bending waveguide, both polarizations show negligible pure bending losses and exhibit similar performances for the transition loss. Therefore, the present deeply-etched SiO$_2$ waveguides possess the potential to realize compact polarization-independent PLCs.

D. MMI Couplers

MMI devices [15] are widely used in modern wavelength division multiplexing (WDM) systems due to their excellent performance, such as broadband operation, relaxed fabrication requirements, etc. Here we fabricated and characterized MMI couplers based on the deeply-etched SiO$_2$ waveguide to explore its practical applications. Fig. 11 shows the transmission characteristics (normalized to the transmission of a straight waveguide with the same length) of the $1 \times 2$, $1 \times 4$, and $1 \times 8$ MMI couplers. For these MMI couplers, the widths of the input/output waveguides were chosen to be 2.5 $\mu$m. The sizes of the MMI couplers based on the deeply-etched waveguides were greatly reduced due to the strong lateral confinement. For example, the footprint of the present $1 \times 4$ MMI coupler was only about 1/6 of its counterpart based on conventional buried SiO$_2$ waveguides. The microphotograph of a fabricated $1 \times 4$ MMI coupler is shown in the inset of Fig. 11, where the residual metal mask was not removed after etching and remained on top of the waveguide. One sees that these MMI couplers have fairly large bandwidths and moderate losses. At $\lambda = 1550$ nm, the average transmission of all channels and non-uniformity of each MMI coupler are summarized in Table II. One sees that the average transmission is reduced almost by 3 dB when the number of output ports doubles, as expected. The non-uniformity increases gradually as the number of output ports increases. The losses were mainly caused by the deviation of the waveguide geometry from the design due to the fabrication imperfection. Since the sidewall of the waveguide was not vertical, the practical propagation constants of the modes in the multimode region deviated from the designed values. Then the imaging positions did not coincide with the positions of the output waveguides. Furthermore, due to the lag effect [16], [17] during etching, the etching depth is smaller for a denser pattern. Thus, the output waveguides had a shallower etching and consequently were not separated completely at their ends connected to the MMI section. The coupling between adjacent output waveguides was therefore enhanced, which introduced some excess loss and non-uniformity. This imperfection of geometry due to the lag effect during etching could be improved by optimizing the process towards deep etching of a high aspect ratio [18].

IV. Conclusion

In this paper, we have fabricated and characterized deeply-etched SiO$_2$ ridge waveguides. The fabrication process (especially for the deep etching process) is described and discussed in detail. The propagation loss of the waveguide is mainly caused by the sidewall scattering and leakage towards substrate. The fabricated waveguide exhibits a good bending ability due to the strong lateral confinement and it can be foreseen that the bending radius can be reduced to several tens of microns when an optimized fabrication process and optimal waveguide parameters are used. By using the present deeply-etched SiO$_2$ ridge waveguide, we have also demonstrated $1 \times 2$, $1 \times 4$, and...
1 x 8 MMI couplers with fairly good performances and compact sizes. These experimental results have shown that this kind of waveguide is a promising candidate to realize compact PLCs in a broad wavelength range from visible light to infrared.

In order to reduce the propagation loss for the present deeply-etched SiO₂ ridge waveguide, one could increase the refractive index contrast between the core and buffer [3]. In this way, the thicknesses of both the core and buffer layers can be reduced and a deep-etching could be relaxed. This is helpful in reducing the sidewall roughness. We note that the most important thing to achieve a low propagation loss is to optimize the etching process and obtain smooth and vertical sidewalls. This may need advanced process facilities, such as Advanced Oxide Etch (AOE) equipment [18].

Fig. 11. The transmission of MMI couplers based on the deeply-etched SiO₂ waveguides. Inset: The micrographic photograph of a fabricated 1 x 4 MMI coupler, in which the width of the multimode region is 45 μm.

Table II

<table>
<thead>
<tr>
<th>1 x 2 MMI</th>
<th>1 x 4 MMI</th>
<th>1 x 8 MMI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average transmission (dB)</td>
<td>-6.06</td>
<td>-9.17</td>
</tr>
<tr>
<td>Non-uniformity (dB)</td>
<td>0.45</td>
<td>0.63</td>
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</table>

References

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Fabrication and characterization of suspended SiO$_2$ ridge optical waveguides and the devices

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Abstract: Novel suspended SiO$_2$ ridge optical waveguides on silicon are fabricated and characterized. The present suspended SiO$_2$ ridge optical waveguide has a SiO$_2$ ridge core surrounded by air. The propagation loss and the bend loss measured are about 0.385dB/cm and 0.037dB/90° respectively for the fabricated 1.541μm-wide waveguides with a bending radius of 100μm when operating at the wavelength of 1550 nm. With the present suspended SiO$_2$ optical waveguides, a small racetrack resonator with a radius of 100μm is also demonstrated and the measured Q-factor is about 3160.

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OCIS codes: (220.4601) Optical fabrication; (230.3120) Integrated optics devices.

References and links
1. Introduction

The demand of photonic integrated circuits (PICs) keeps increasing for optical communication, optical interconnects as well as optical sensing. In order to satisfy the demands, various material systems and optical waveguide types have been developed, like LiNbO$_3$ [1], silica [2–5], silicon-on-insulator [6–8], III–V semiconductor [9, 10], and polymers [11].

Among them, silicon-on-insulator (SOI) provides a good platform to have ultra-dense PICs by utilizing SOI nanowires which have a submicron cross section and ultra-high index-contrast [6, 12]. Thus, silicon photonics has been deeply developed in the past years for optical interconnects [13], as well as optical sensing [14, 15]. However, because silicon is not transparent in the wavelength range of less than 1.1 $\mu$m [4], SOI nanowires do not work in the visible range, which is very important for some applications like optical.

In contrast, silica is one of the most attractive materials for passive PICs because of its mature fabrication process, as well as low propagation loss. One of the most popular silica optical waveguide is the SiO$_2$-on-Si buried rectangular waveguides which has a low index-contrast ($\Delta$~0.75%) and a Ge-doped core as large as size 6 × 6 $\mu$m$^2$ so that it has high coupling efficiency with a single mode fiber [3]. However, for a conventional SiO$_2$-on-Si buried rectangular waveguides, the bending radius is as large as some millimeters even centimeters [5], due to its low index-contrast ($\Delta$). This is not good for the future dense PICs. Besides, the buried SiO$_2$-on-Si waveguide is also not a good option for optical sensing because the cladding prevents the medium to contact the evanescent field.

A deeply-etched SiO$_2$ optical waveguide is a potential choice for solving these issues because it has an air cladding so that it enables sharp bending as well as optical sensing with relatively high-sensitivity [4, 5, 16]. However, it requires very deep etching (~16 $\mu$m or more), which makes it not easy to achieve a low-loss light waveguiding because the deeply-etched sidewall is relatively rough.

In the present paper, we propose a novel suspended SiO$_2$ optical waveguide on silicon substrate so that it could work in a broad wavelength band ranging from the visible light to the infrared light. Suspended optical waveguides have been demonstrated before with the materials of silicon [17], III–V semiconductor [10, 18], etc. Ultra-high Q suspended micro-disks on silica has been also demonstrated [19]. Kei Watanabe, et al realizes ultralow power consumption silica-based PLC-VOA switches using suspended narrow ridge structure [20]. Our proposed suspended SiO$_2$ optical waveguide has a small SiO$_2$ ridge region surrounded by air, which introduces a relatively high index-contrast $\Delta$ and consequently enables the bending radius as small as 100 $\mu$m (or smaller). The surrounding air region also makes it very attractive for optical sensing. Furthermore, for the present suspended SiO$_2$ optical waveguides, only a layer of SiO$_2$ thin film whose thickness is around 1 $\mu$m is needed to be formed on a silicon substrate. This makes the fabrication very simple and cheap potentially because a simple and
short-time thermal oxidation process is enough for forming the SiO$_2$ thin film and a shallowly etching is needed only. In contrast, for the conventional SiO$_2$-on-Si buried rectangular waveguide and the structure in [20], which has ~40μm-thick SiO$_2$ films (including an under-cladding, a core region as well as an upper-cladding), one needs some expensive technologies. For example, in order to form the thick SiO$_2$ film, one usually needs the plasma-enhanced chemical vapor deposition (PECVD) or flame hydrogen deposition (FHD) technologies, and Ge-doping is required for the core layer with a higher index than the cladding layer. Furthermore, the deep etching technology is also needed. In this paper, we have designed and fabricated the proposed suspended SiO$_2$ optical waveguides as well as race-track resonators as an example.

2. Structure and fabrication of the suspended SiO$_2$ optical waveguide

Figure 1(a) shows the cross section of the proposed suspended SiO$_2$ ridge optical waveguide, which has an air-cladded SiO$_2$ ridge core on a silicon substrate. The air under-cladding is formed by removing the silicon beneath partially by using a second ICP dry etching process with the gases SF$_6$, O$_2$, CHF$_3$ after the windows in the slab layer are open, as shown in Fig. 1(b). The slab layer is a very important part not only for forming a ridge waveguide but also supporting the suspended waveguides. It can be seen that silicon substrate is not removed in the region far away from the ridge so that the slab could be supported by the Si substrate. Therefore, the slab thickness should be thick enough to have good mechanical strength. In our design, we choose the slab thickness $h$ to be around 300nm. The height $h_r$ of the air under-cladding is determined by the time of dry etching process. From Fig. 1(b), it can be seen that there are a row of windows at each side of the ridge. The distance $d_{win}$ between the window edge and the ridge edge should large enough so that the light propagation along the ridge waveguide does not be influenced by the windows. According to the mode profile shown in Fig. 1(c), which gives the calculated TE-polarization mode profiles for a 1μm-wide straight waveguide, one sees that the distance $d_{win}$ should be larger than e.g., 4μm. In our case, we choose $d_{win} = 7μm$ as an example (see Fig. 1(b)). Here the waveguide parameters are chosen as follows: the SiO$_2$ refractive index $n_{SiO_2} = 1.444$, the ridge width $w_{co} = 1μm$, the ridge height $h_r = 660nm$, the slab height $h = 310nm$. Figure 1(d) shows the pure bending loss and the transition loss as the radius varies. One can see that the bending loss and transition loss is very small when the radius is 100μm.

Figure 2 shows the fabrication process for the present SOW. First, a thin SiO$_2$ film is formed on a <100> silicon substrate. It is well known that there are many ways to form a SiO$_2$ film, e.g., using the plasma-enhanced chemical vapor deposition (PECVD) technology [2–4,
the flame hydrolysis deposition (FHD) technology [22], as well as the thermal oxidation [3]. The former two are very popular for forming very thick SiO₂ film, however, which usually is porous (not dense). Consequently the mechanical strength is not strong enough for our present suspended waveguide. In contrast, the thermal oxidation method is pretty good and low-cost choice to form dense SiO₂ thin film with very good mechanical robustness. The drawback is that the SiO₂ thickness formed by the dry thermal oxidation is usually no more than 1~2μm and the rate is very slow. It takes 8h to grow about 400nm at normal pressure and 1050°C with dry thermal oxidation. For the present case, the SiO₂ film is as thin as only hundreds of nanometers. Therefore, we choose wet thermal oxidation process to form SiO₂ thin film on a silicon substrate. In our fabrication, a ~970nm-thick SiO₂ film is formed through two-hour wet thermal oxidation (i.e., the O₂ heated in 98°C hot water) at normal pressure and the temperature is around 1100°C. Then electron-beam negative electron-resist (ma-N 2405) is spin-coated on the ~970nm-thick SiO₂ thin film. The thickness of the photoresist film is about 470nm at the spinning speed of 3000rpm (See Fig. 2(a)). The sample with the electron-beam negative electron-resist is then baked (90 second @ 90°C) to evaporate the solvent. Then the pattern is generated by using the Raith150-two ultra-high resolution E-beam writer. After the development (See Fig. 2(b)), a dry-etching with the STS ICP (Inductive Coupled Plasma) etching system is proceeded to etch the SiO₂ thin film (See Fig. 2(c)). Fluorine-based gas such as CF₄ and CHF₃ is used for this dry etching process. Then a SiO₂ rib optical waveguide is formed on silicon substrate. In order to remove Si beneath the SiO₂ optical waveguide, we open some rectangular windows about 5 × 7μm² at both sides of the SiO₂ ridge (the distance is about 7μm) with a second lithography (Fig. 2(d)) and dry-etching process. Si beneath the SiO₂ optical waveguide is then removed by using ICP dry etching with the gases such as SF₆, O₂ and CHF₃ through the open windows, as shown Fig. 2(e). In order to remove the residual Si, we soaked the sample in the TMAH (with a concentration of 10 wt%) at the temperature of 85°C for about 10min. Finally, we soak the Si wafer in H₂SO₄ and H₂O₂ mixed solution to remove the residual photoresist and fluorocarbon formed during the etching process.

Figure 2. The fabrication process for our suspended optical waveguide.

Figure 3(a)-(d) show the SEM (scanning electron microscope) pictures for the fabricated suspended waveguides and structures. Figure 3(a) shows the coupling region consisting of two paralleled suspend optical waveguides for a racetrack resonator. Figure 3(b)-(c) shows the sidewall and the cross section of the fabricated suspended optical waveguide, respectively. From Fig. 3(b), it can be seen that the waveguide has quite smooth sidewalls, which is beneficial to obtain a low propagation loss. From cross section of the fabricated suspended optical waveguide shown in Fig. 3(c), it can be seen clearly that the silicon substrate beneath the waveguide ridge is removed. The height of the air region under the silica ridge is about 20μm, which could be varied by controlling the time of ICP etching with SF₆. It can also be seen that there is significant buckling in the SiO₂ after it is released from the from the silicon, which is due to the high temperature during oxidation around 1100°C [23], as shown in Fig. 3(c). The estimated stress is about 1.2 × 10⁹ dyn/cm² according to the result given in [23]. This caused a large coupling loss partially due to the numerical aperture mismatch when light
is coupled between a fiber and the waveguides, which will be seen from the measured loss given below.

Fig. 3. SEM pictures of the structures. (a) the top view for the coupling region of a racetrack resonator. The waveguide width \( w = 1\mu m \), and the gap width \( w_{\text{gap}} = 1\mu m \); (b) a straight waveguide; (c) the cross section of a fabricated waveguide; (d) the enlarged view for the cross section.

3. Characterization of the fabricated suspended SiO\(_2\) optical waveguides and devices

A bent waveguide is one of the basic elements for various PICs. It is desirable to achieve a small bending radius with low bend loss especially for dense PICs. For the present suspended SiO\(_2\) optical waveguide, small bending radius is expected because of its relatively high index-contrast. In order to measure the propagation loss as well as the bending loss of the suspended SiO\(_2\) optical waveguides, we have designed a series of spiral structures with different lengths. All the bends in the spiral structure has the same radius of 100\(\mu m\), as shown by the inset in Fig. 4. A tunable laser is used for the measurement and a lens fiber is used to couple the light into the suspended optical waveguide. Since the measured total loss \( L_{\text{tot}} \) is not sensitive to the wavelength in the C-band, we only show the measured total losses \( L_{\text{tot}} \) at 1550nm for these spirals in Fig. 4. The total loss for a spiral waveguide is given by \( L_{\text{tot}} = L_s I + N L_B + 2L_c \), where \( L_s \) is the propagation loss per unit length, \( I \) is the total length of the spiral, \( N \) is the 90\(^\circ\)-bend number, \( L_B \) is the bend loss, and \( L_c \) is the coupling loss per facet between a fiber and the suspended waveguide. In order to extract the loss values, we assume that the bending section has the same propagation loss \( L_s \) over a unit length (dB/cm) as the straight waveguide while the bending section has an addition pure bending loss (i.e., \( L_B \)). Such an assumption is reasonable for the present case because the bending radius is very large so that the mode field profile in the bending section is very similar with that in the straight section. With such an assumption, we extracted the value for the losses \( L_s, L_B \), and \( L_c \) by fitting the measured data shown in Fig. 4 with the least square method. Finally we obtain \( L_s = 0.38\text{dB/cm} \), \( L_B = 0.037\text{dB/90}^\circ \) and \( L_c = 17.6\text{dB/facet} \). The large coupling loss comes from the following sources. The first source is from the mode mismatch loss between the lens fiber and the suspended waveguide. For the present case, the lens fiber and the suspended waveguide have diameters of about 3–4\(\mu m\) and 1\(\mu m\), respectively. Consequently the estimated mode mismatching loss is about 10dB. The second source for the coupling loss is the loss due to the facet reflection, which is about 0.236dB. The third source is the waveguide bending at the facet due to the thermal strain, as shown in Fig. 3(b).

Regarding that a ring resonator is an essential versatile block for various functionalities like optical modulators [7], optical logic and switch [8, 9], optical sensors [14, 15], wavelength filters [24], power splitters [25], lasers [26], and so on, we design and fabricate a race-track resonator with our proposed suspended SiO\(_2\) optical waveguide, as shown in the inset of Fig. 5(b). The length for the coupling region is chosen as \( L_{\text{dc}} = 200\mu m \), the gap width is \( w_{\text{gap}} = 1\mu m \), and the bending radius \( R = 100\mu m \). Figure 5 shows the measured spectral
responses at the through port of the fabricated racetrack resonators. The insert shows the SEM picture for the fabricated racetrack resonator. There are many small square windows locating at both sides of the waveguide (inside as well as outside of the racetrack) for partially removing the silicon substrate beneath. From this figure, it can be seen that the FSR is about 1.5nm, which is very close to the theoretical prediction. The extinction ratio is about 20dB, and the 3dB bandwidth is about 0.48nm, which corresponds to a loaded Q factor of about 3200. This relatively low loaded Q-value is mainly due to the large coupling ratio between the resonator and the access waveguides. It is possible to enhance the Q-factor by improving the design and fabrication of the coupling region.

**Fig. 4.** The transmission for the suspended waveguides with different lengths. Inset is the micrographic photograph of a spiraled waveguide for measuring propagation loss and bend loss.

**Fig. 5.** The measured spectral response at the through port of the fabricated racetrack resonator. Inset is the SEM picture of the fabricated race-track resonator.

### 4. Conclusion

In this paper, we have designed and fabricated novel suspended optical ridge waveguides on silica. The measured propagation loss and bending loss are about $L_s = 0.38$dB/cm, and $L_B = 0.037$dB/90°, respectively. A racetrack resonator has been also fabricated by using the proposed novel suspended optical waveguide. It has shown that the fabricated racetrack ring resonance has shown that the present suspended waveguide can be used to realize compact PICs in comparison with those traditional buried silica waveguides and the performance can be improved with the optimized fabrication process and waveguide parameters.

**Acknowledgments**

This project was partially supported by the National Nature Science Foundation of China (No. 61077040), a 863 project (Ministry of Science and Technology of China, No. 2011AA010301), Zhejiang provincial grant (Z201121938, No. 2011 C11024) of China, and also supported by the Fundamental Research Funds for the Central Universities.
Sensitivity Enhancement in Si Nanophotonic Waveguides Used for Refractive Index Sensing

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Academic Editor: Vittorio M. N. Passaro
Received: 6 January 2016; Accepted: 29 February 2016; Published: 3 March 2016

Abstract: A comparative study is given for the sensitivity of several typical Si nanophotonic waveguides, including SOI (silicon-on-insulator) nanowires, nanoslot waveguides, suspended Si nanowires, and nanofibers. The cases for gas sensing \( (n_{\text{cl}} \approx 1.0) \) and liquid sensing \( (n_{\text{cl}} \approx 1.33) \) are considered. When using SOI nanowires (with a SiO\(_2\) buffer layer), the sensitivity for liquid sensing \( (S \approx 0.55) \) is higher than that for gas sensing \( (S \approx 0.35) \) due to lower asymmetry in the vertical direction. By using SOI nanoslot waveguides, suspended Si nanowires, and Si nanofibers, one could achieve a higher sensitivity compared to sensing with a free-space beam \( (S = 1.0) \). The sensitivity for gas sensing is higher than that for liquid sensing due to the higher index-contrast. The waveguide sensitivity of an optimized suspended Si nanowire for gas sensing is as high as 1.5, which is much higher than that of a SOI nanoslot waveguide. Furthermore, the optimal design has very large tolerance to the core width variation due to the fabrication error \( (\Delta w \approx \pm 50 \text{ nm}) \). In contrast, a Si nanofiber could also give a very high sensitivity \( (e.g., \approx 1.43) \) while the fabrication tolerance is very small \( (i.e., \Delta w < \pm 5 \text{ nm}) \). The comparative study shows that suspended Si nanowire is a good choice to achieve ultra-high waveguide sensitivity.

 Keywords: sensitivity; silicon; nanowire; nanoslot; nanofiber

1. Introduction

Optical waveguide sensors are paving the way for realizing low-cost, highly sensitive, ultra-compact optical sensors, which are desired for many applications such as biological, environmental and chemical detections [1–9]. It is also easy to have a sensor array based on optical waveguides. Usually, the principle of optical waveguide sensors is based on the perturbation of the field of a guided mode caused by optical absorptions, fluorescence or refractive index changes of the measured sample [8]. Among them, refractive index sensors are popular because of their easy realization, and the potential for real-time monitoring with a minimal sample volume. When the concentration of the sample covering on the waveguide surface changes, the effective refractive index of the optical waveguide changes and consequently a phase shift will be introduced. This phase shift could be converted into an intensity change or a frequency shift using interferometers or resonant structures. In past years, people have developed various integrated optical sensors based on different structures and mechanisms, e.g., Mach–Zehnder interferometers (MZI) [1], and high-Q optical microcavities (including microrings/microdisks [2–11]).

When designing and fabricating an optical sensor, sensitivity is one of the most important figures of merit to consider. Generally speaking, there are two parts contributing to the total sensitivity, i.e., the waveguide sensitivity \( (S_{\text{WG}}) \) and the device sensitivity \( (S_d) \) [11]. The device sensitivity is the ratio of the change in the measured optical parameter \( (i.e., \text{the resonance wavelength, or the intensity at a} \)
specific wavelength) to the change of the effective index. The waveguide sensitivity $S_{WG}$ is defined as the ratio of the effective index change $\Delta n_{eff}$ to the change $\Delta n_s$ of the sample index, i.e., $S_{WG} = \Delta n_{eff}/\Delta n_s$.

In order to improve the sensitivity of an optical sensor, one should improve the device design as well as the waveguide design. The device sensitivity $S_d$ mainly depends on the device structure while the waveguide sensitivity $S_{WG}$ depends on the waveguide cross section as well as the refractive index profile. One can optimize the device structure and the waveguide structure separately to maximize the device sensitivity and the waveguide sensitivity, respectively. For example, an ultra-high sensitivity was achieved using the Vernier effect in a dual-ring system [12–14], and the waveguide sensitivity can be improved using some special waveguides, which will be discussed in this paper.

Since only the evanescent field (which is a small part of the total guided-modal field) “experiences” the analyzed medium, the sensitivity $S_{WG}$ of a guided mode in an optical waveguide is usually assumed to be smaller or much smaller than that of a free-space beam ($S = 1$) [15]. This is true when using a conventional strip or rib waveguide with a large core size and a low index-contrast because the evanescent fields are not very strong. For example, the sensitivity for a SiO$_2$ or polymer waveguide is usually less than 0.1 [1], which is much smaller than that of a free-space beam. Hollow-core waveguides [16] are developed to obtain a higher sensitivity in the way of guiding light in the low-index sample material using the Bragg-grating effect. However, this also makes the waveguide transmission highly wavelength dependent and furthermore the fabrication is quite complicated.

Recently, Si nanowires have become a favored choice because of their evanescent field enhancement in the cladding region due to the small cross section and the ultra-high index contrast. TM polarization is usually used to have higher sensitivity, $S_{WG} \approx 0.5$ [1], which, however, is still less than that of a free-space beam ($S = 1$). In 2004, a nanoslot waveguide was introduced as a novel guided-wave configuration [17], in which there is a field enhancement in the low-index slot region due to the boundary condition of the perpendicular electrical component. This makes it very attractive to achieve high sensitivity for optical sensing [18–20]. For a nanoslot waveguide, the optimized waveguide sensitivity could be as high as 1.0 [19,20], which provides a way to realizing a waveguide sensitivity of more than the sensitivity of a free-space beam ($S = 1$). In [15], the author gave an analytical analysis for a three-layer slab waveguide and reported a peculiar effect, namely that the waveguide sensitivity can indeed be larger than 1.0 for TM polarization. This means that an optical waveguide sensor can be made with a higher sensitivity than a free-space configuration.

In this paper, we consider the case with three-dimensional nanophotonic waveguides and give a comparative study for the sensitivity of several typical silicon nanophotonic waveguides with a very-high index-contrast, e.g., SOI (silicon-on-insulator) nanowires, SOI nanoslot waveguides, suspended Si nanowires, and Si nanofibers. Our simulation shows that an enhanced sensitivity of about 1.5 could be achieved by using suspended Si nanowires.

2. Analysis and Discussion

In this paper, we consider several typical Si nanophotonic waveguides operating at 1550 nm. The involved materials for nanophotonic waveguides include Si, SiO$_2$, and gas (or liquid), whose refractive indices are assumed to be 3.455, 1.445, and 1.0 (or 1.33), respectively. In this paper, we assume that the buffer layer in various SOI optical waveguides considered here is thick enough to make the substrate leakage negligible. For example, the thickness of the SiO$_2$ buffer layer is 3 $\mu$m in the following calculation.

2.1. SOI Nanowires

In this part, we consider a SOI nanowire, which has a Si core and a SiO$_2$ buffer layer, as shown in Figure 1a, which is the most popular one used for optical sensing [1]. The upper-cladding is the sample to be measured (i.e., $n_s = n_{cl}$), which is a gas ($n_s = n_{cl} \approx 1$) or liquid ($n_s = n_{cl} \approx 1.33$). TM polarization is considered in the following calculation. Figure 1b shows the calculated field distribution of the TM
fundamental mode for a Silicon nanowire waveguide with $h_{co} = 250 \text{ nm}$, $w_{co} = 350 \text{ nm}$, $n_{cl} = 1.0$ as an example.

Figure 1c shows the calculated sensitivity as the core width $w_{co}$ varies from 0.1 $\mu$m to 0.8 $\mu$m when the upper-cladding is filled with gas ($n \sim 1.0$). The Si core layer is 220, 230, 240, 250, 260, 270, 280, 290, 300, 350, and 400 nm thick, respectively. For the case with a relatively thick core (e.g., $h_{co} \geq 350 \text{ nm}$), the sensitivity is low, especially when the core width is large. This is because most power of the fundamental mode is confined in the core region while the evanescent field is very small, as shown in Figure 1d, where $P_{co}$, $P_{cl}$, and $P_{buffer}$ are the power confinement ratio in the regions of core, upper-cladding, and buffer, respectively. When the core width decreases, the confinement becomes weaker and more evanescent field penetrates to the upper-cladding (see Figure 1d). The sensitivity consequently increases, as shown in Figure 1c.

On the other hand, one should note that the present waveguide is asymmetrical in the vertical direction, i.e., the upper-cladding (gas) has a lower refractive index than the buffer layer (SiO$_2$). Therefore, when the core becomes very narrow, the optical waveguide cannot confine the optical field well and less power is confined in the upper-cladding region, while more power moves to the SiO$_2$ buffer region (see Figure 1d). For example, when $w_{co} = 140 \text{ nm}$, the power ratios in the regions of Si core, SiO$_2$ buffer, and gas upper-cladding are 25.4%, 41.6%, and 32.9%, respectively. Thus, the sensitivity becomes smaller as the core width decreases further. This explains the existence of an optimal core width $w_{opt}$ for a maximal sensitivity when the core width varies in Figure 1c. For example, when $h_{co} = 400 \text{ nm}$, the maximal sensitivity $S_{\text{max}} = 0.441$ when choosing the optimal core width $w_{opt} = 130 \text{ nm}$. However, the sensitivity decreases significantly when the core width deviates from the optimal value. Furthermore, such a SOI nanowire with a high aspect ratio is not a good option when considering the fabrication (e.g., the etching process) and the scattering loss. When choosing a thinner SOI nanowire, there is also an optimal core width $w_{opt}$ for maximal sensitivity. A significant decrease of the sensitivity is also observed when choosing a core width much smaller than the optimal width $w_{opt}$. And the sensitivity around $w = w_{opt}$ is less dependent on the core width in comparison to the case with a large thickness (e.g., $h_{co} = 400 \text{ nm}$). Therefore, one could achieve high sensitivity when the core width varies in a large range around $w_{opt}$.

From Figure 1c, we also observe that the sensitivity curve for thin SOI nanowires is discontinuous as the core width decreases from 0.8 $\mu$m to 0.6 $\mu$m. This is due to the mode hybridization in that width range. In order to explain this, Figure 1d shows the effective index of an SOI nanowire with $h_{co} = 250 \text{ nm}$ as the core width varies. From this figure, it can be seen that there is a region (see the circle in Figure 1e) around $w_{co} = 700 \text{ nm}$, where the TM fundamental mode (TM$_0$) and the first-order mode of TE polarization (TE$_1$) are hybridized. Therefore, when we consider the sensitivity of TM$_0$, a jump appears, as shown in Figure 1c. As can be seen, higher sensitivity $S_{\text{WC}}$ can be achieved when choosing the waveguide width around the mode hybridization region. However, when higher-order modes are involved, there might be some undesired multimode effect. For example, when using a microring-resonator sensor, more resonance peaks will appear and the Q-factor will degrade. Therefore, we still focus on the singlemode silicon optical waveguides for optical sensing. Here we also calculate the sensitivity for SOI nanowires with a liquid cladding ($n \sim 1.33$), which is very popular for biosensing. Figure 1f shows the calculated sensitivity, which is similar to the case for the gas sensing (see Figure 1c). When there is a liquid cladding, the optical waveguide becomes less asymmetrical because the liquid index is closer to that of the SiO$_2$ buffer layer. Therefore, less power is confined in the SiO$_2$ buffer region and more power is confined in the upper-cladding region, as shown in Figure 1g. Thus, more evanescent optical fields interact with the sample and consequently the sensitivity of a SOI nanowire becomes higher for liquid sensing than that for gas sensing (see Figure 1c,f).
Figure 1. (a) The cross section of a SOI nanowire; (b) the calculated field distribution of the TM fundamental mode for a Silicon nanowire waveguide with $h_{co} = 250$ nm, $w_{co} = 350$ nm, and $n_{cl} = 1.0$; (c) the calculated waveguide sensitivity as the core width varies when the upper cladding is filled with gas ($n \approx 1.0$); (d) the power confinement ratio in the regions of core ($P_{co}$), upper-cladding ($P_{cl}$), and buffer ($P_{buffer}$); (e) the effective indices of the eigenmodes for a SOI nanowire with $h_{co} = 250$ nm; (f) the calculated sensitivity as the core width varies when the upper cladding is filled with liquid ($n \approx 1.33$); and (g) the power ratio in the regions of core ($P_{co}$), upper-cladding ($P_{cl}$), and buffer ($P_{buffer}$) when $h_{co} = 250$ nm.
2.2. SOI Nanoslot Waveguides

An SOI nanoslot waveguide consists of two Si regions with a nanoslot between them, as shown in Figure 2a. Figure 2b shows the calculated field distribution of the TE fundamental mode for a SOI nanoslot waveguide with \( h_{co} = 400 \) nm, \( w_{co} = 180 \) nm, and \( w_s = 30 \) nm as an example. It can be seen that there is a significant field enhancement in the nanoslot region. This field enhancement makes it very attractive for optical sensing when the sample to be measured fills the whole region of upper-cladding (including the nanoslot region).

Figure 2c–f show the calculated waveguide sensitivity for gas sensing as well as liquid sensing as the core width \( w_{co} \) varies for the cases of \( h_{co} = 400, 350, 300, \) and \( 250 \) nm, respectively. The nanoslot width is chosen as 100, 80, 60, 50, 40, and 30 nm for any given core height \( h_{co} \). In Figure 2c–f, it can be seen that the sensitivity of a nanoslot waveguide is similar for different values of \( h_{co} \) when it is covered by gas or liquid. For a nanoslot waveguide with a given slot width \( w_s \) and core height \( h_{co} \), the sensitivity increases rapidly and then decreases slightly as the core width varies in the range from \( 0.12 \mu m \) to \( 0.24 \mu m \). It can be seen that there exists an optimal core width \( w_{opt} \) for obtaining a maximal sensitivity \( S_{max} \) for both cases based on claddings of gas and liquids.

When the core width becomes small (e.g., \( w_{co} = 0.1 \mu m \)), the optical confinement is very weak and the power at the under-cladding becomes dominant due to the vertical asymmetry, especially in the case with a gas cladding. In this case, the optical waveguide become insensitive to the index change of the upper-cladding. In contrast, when there is a liquid cladding, the vertical asymmetry is alleviated and consequently the sensitivity is still relatively high even when the Si core width is reduced to \( 0.1 \mu m \). On the other hand, when the core width becomes larger (e.g., \( 0.24 \mu m \)), the optical confinement becomes stronger and more power is confined in the Si core region, and consequently the field enhancement in the nanoslot is significantly limited. Therefore, the sensitivity of the nanoslot optical waveguide decreases as the core width increases.

![Figure 2. Cont.](image-url)
Figure 2. (a) The cross section of a nanoslot optical waveguide; and (b) the calculated field distribution of the TE fundamental mode for a SOI nanoslot waveguide with $h_{co} = 400$ nm, $w_{co} = 180$ nm, and $w_s = 30$ nm as an example. The calculated sensitivity for gas sensing and liquid sensing as the core width varies for the cases with different core heights: (c) $h_{co} = 400$ nm; (d) $h_{co} = 350$ nm; (e) $h_{co} = 300$ nm; and (f) $h_{co} = 250$ nm.

We also note that a nanoslot waveguide with a larger core height gives a higher maximal sensitivity, which could be larger than that of a free-space beam ($S = 1$). This is because a larger optical field overlaps with the upper-cladding when the core height increases. In contrast, when the core height turns small, more power moves down to the SiO$_2$ under-cladding because of the asymmetry in the vertical direction. From Figure 2c–f and Figure 1b, it can be seen that nanoslot waveguides have a much higher sensitivity than conventional SOI nanowires.

2.3. Suspended Si Nanowires

In this part, we give an analysis for a suspended Si nanowire, which includes a Si core surrounded by the sample, as shown in Figure 3a. Such a suspended waveguide could be achieved with supported arms [21,22]. Figure 3b shows the calculated field distribution of the TM fundamental mode for a suspended Si nanowire waveguide with $h_{co} = 220$ nm, $w_{co} = 525$ nm, and $n_{cl} = 1.0$ as an example. Figure 3c shows the calculated sensitivity for a suspended Si nanowire with different core heights $h_{co}$ as the core width varies from 0.1 $\mu$m to 0.8 $\mu$m. From this figure, it can be seen that the sensitivity is slightly higher than 1.0 (i.e., the sensitivity of free space) when the core height is small (e.g., 150 nm). This is because the power confined in the Si core is very small while most power of the guided mode locates at the surrounded media, which is very similar to the free space case.

When the core height becomes larger, a significant sensitivity enhancement is observed. For a suspended Si nanowire with a fixed core height (e.g., $h_{co} = 100 \sim 200$ nm), the sensitivity increases monotonously when the core width ranges from 0.1 $\mu$m to 0.8 $\mu$m. When increasing the core height further (e.g., $h_{co} = 250, 240, 230, 220, and 210$ nm), one sees that in the range of 0.1 $\mu$m < $w_{co}$ < 0.8 $\mu$m there exists an optimal core width $w_{co}$, which gives a maximal sensitivity $S_{\text{max}}$ of >1.0).

In order to explain this, one can use the formula for the sensitivity of a three-layer slab optical waveguide given in [15], i.e.,

$$S = \frac{n_{eff}}{n_{cl}} \left( 2 - \frac{n_{cl}^2}{n_{eff}^2} \right) \frac{P_{cl}}{P_{tot}}$$

where $n_{eff}$ is the effective index, $n_{cl}$ is the index of the cladding, and $P_{cl}/P_{tot}$ is the power confinement ratio in the cladding region. In Figure 3d, we show the power confinement ratio in the regions of core and cladding. In this figure, one sees that the power confinement ratio in the cladding region increases monotonously as the core width decreases, which is easy to understand. Intuitively speaking, one expects to have a higher sensitivity when more power is confined in the cladding region. However,
according to Equation (1), the sensitivity depends not only on the ratio of $P_{cl}/P_{tot}$ but also the ratio of $n_{eff}/n_{cl}$. When the core width decreases, the ratio $P_{cl}/P_{tot}$ increases while the ratio $n_{eff}/n_{cl}$ decreases, which causes an optimal core width for obtaining a maximal sensitivity.

One can imagine that a wide suspended waveguide should have similar result with a slab waveguide. Figure 3e gives a comparison between the calculated sensitivities for a suspended Si nanowire with $w_{co} = 0.8 \mu m$ and $w_{co} = \infty$ (slab waveguide). Here, the results for the slab waveguide ($w_{co} = \infty$) is calculated with Equation (1). It can be seen that these results are quite similar and there is an optimal core height $h_{co}$ around $h_{co} = 220$ nm for the maximal sensitivity. For the suspended waveguide with a given core height $h_{co}$, Figure 3c shows that the optimal core width for the maximal sensitivities $S_{max}$ are slightly dependent on the core height. One should choose $h_{co} = 220$ nm to maximize the sensitivity and the corresponding maximal sensitivity $S_{max}$ is close to 1.5, which is much higher than 1.0 (which is the sensitivity in a free space system). The design of $h_{co} = 220$ nm also has a large tolerance to the variation of the core width. Even when the core width deviates from its optimal value $w_{co, opt} (= 0.525 \mu m)$, the sensitivity does not decrease much. In comparison with the sensitivity for a SOI nanoslot waveguide (shown in Figure 2c–f), the suspended Si nanowire could provide a much higher sensitivity even though it does not have a field enhancement in the low-index region. Such a significant sensitivity enhancement in a suspended Si nanowire makes it very attractive for the application of optical sensing, especially since it is also relatively easy to fabricate.
Figure 3. (a) The cross section of a suspended Si nanowire; (b) the calculated field distribution of the TM fundamental mode for a suspended Si nanowire waveguide with $h_{co} = 220 \text{ nm}$, $w_{co} = 525 \text{ nm}$, and $n_{cl} = 1.0$; (c) the sensitivity of a suspended Si nanowire for gas sensing ($n_{cl} \sim 1.0$); (d) the power confinement ratio in a suspended Si nanowire for gas sensing; (e) the calculated sensitivities for a suspended Si nanowire with $w_{co} = 0.8 \mu\text{m}$ and $w_{co} = 8$ (slab waveguide); (f) the sensitivity of a suspended Si nanowire for liquid sensing ($n_{cl} \sim 1.33$); and (g) the power confinement ratio in a suspended Si nanowire for liquid sensing.

Figure 3f shows the sensitivity of a suspended Si nanowire for liquid sensing (i.e., $n_{cl} \sim 1.33$). Figure 3g shows the power confinement ratios in the regions of core and cladding. It can be seen that the results are similar to those for gas sensing (i.e., $n_{cl} \sim 1.0$). The power ratio in the cladding region is higher because of the lower index-contrast. However, the maximal sensitivity is lower when there is a higher cladding index, as predicted in Equation (1).

2.4. Nanofibers

Nanofibers are another candidate for the use as a suspended waveguide for optical sensing. Since Si is considered for the core of the planar nanophotonic waveguides in the analysis above, we also choose nanofibers based on Si. Figure 4a shows the calculated waveguide sensitivity for a Si nanofiber with gas cladding as the core radius $R$ varies from 0.06 \mu\text{m} to 0.3 \mu\text{m}. The inset shows the cross section of the Si nanofiber. From this figure, one sees that there is an optimal core radius giving a maximal sensitivity, which is similar to the result for suspended Si nanowires. This could be explained as follows: when the core radius is small, the optical confinement is very weak and most power of the guided mode is in the cladding. In this case, the nanofiber behaves like in free space sensing. When the
core radius becomes large, the optical confinement becomes very strong. Consequently the evanescent field is very small, which reduces the sensitivity. One might see it in Figure 4a, when it is used for gas sensing, the optimal core radius is about 0.15 μm and the maximal sensitivity $S_{\text{max}}$ is about 1.43, which is slightly lower than that of an optimized suspended Si nanowire (see Figure 3b). In contrast, for the case of liquid sensing, the optimal core radius is about 0.14 μm and the maximal sensitivity $S_{\text{max}}$ is about 1.2.

When one chooses the optimal core radius for the highest sensitivity, care must be taken because of the strong tolerance upon the core radius dimension. For example, when the core radius varies from the optimal value (i.e., 150 nm) to 165 nm, the sensitivity decreases from 1.43 to 0.943 and one has $\Delta S/\Delta R = 32.5/\mu m$ (here $\Delta R$ is the radius variation and $\Delta S$ is the sensitivity decrease). This indicates that one should control the diameter of the nanofiber very carefully in order to achieve the maximal sensitivity. In contrast, the suspended Si nanowire is more tolerant to the lateral dimension variation $\Delta w_{\text{co}}$. For example, when the core width $w_{\text{co}}$ of a suspended waveguide (with $h_{\text{co}} = 220$ nm) varies from the optimal value (i.e., 440 nm) to 455 nm, the sensitivity decreases from 1.477 to 1.475 and one has $\Delta S/\Delta w_{\text{co}} = 0.13/\mu m$, which is ~240 times less than that of a silicon nanofiber. We note that it is still not easy to fabricate Si nanofibers with the dimensions required for the highest sensitivity. On the other hand, it is well known that nanofibers have been fabricated successfully in the past years using SiO₂ or polymer [23]. Figure 4b shows the calculated sensitivity of a SiO₂ nanofiber with air cladding. In this figure, it can be seen that one has a maximal sensitivity close to 1.0 when the core radius of the nanofiber is small. Due to the lower index contrast, one cannot obtain an enhanced waveguide sensitivity of more than 1.0 using SiO₂ or polymer nanofibers.

3. Conclusions

In this paper, a comparative study has been given for the sensitivity of several typical Si nanophotonic waveguides, including SOI nanowires, SOI nanoslot waveguides, suspended Si nanowires, and nanofibers. We have considered two cases of gas sensing ($n_{\text{cl}} \sim 1.0$), and liquid sensing ($n_{\text{cl}} \sim 1.33$). When using SOI nanowires (with a SiO₂ buffer layer), the sensitivity for liquid sensing is higher than that for gas sensing, due to lower asymmetry in the vertical direction. Our calculations have also shown that it is possible to achieve a waveguide sensitivity higher than that of a free-space sensing ($S = 1.0$) using SOI nanoslot waveguides, suspended Si nanowires, or Si nanofibers. Among them, the suspended Si nanowires give the highest sensitivity with an optimized core size. One should note that the fabrication process for suspended Si waveguides is more complex than that of standard SOI nanowires. Fortunately such a suspended waveguide can be achieved with supported arms by utilizing additional etching processes to remove the bottom-buffer layer [4,24,25]. When using an optimized suspended Si nanowire for gas sensing, the waveguide sensitivity could be as high as

![Figure 4](image-url)
1.5, which is much higher than that of a SOI nanoslot waveguide. More importantly, the sensitivity of the optimal suspended Si nanowire decreases only very slightly, even when the core width has some variation (e.g., $\Delta w = \pm 50$ nm). For an optimized Si nanofiber, the sensitivity could be as high as about 1.43, which is close to that of an optimized suspended Si nanowire. However, the tolerance is very small (e.g., the deviation $< \pm 5$ nm) and one has to control the diameter of the nanofiber very carefully. The present comparative study has shown that suspended Si nanowire is a good choice to achieve ultra-high waveguide sensitivity.

**Acknowledgments:** This work was partially supported by the National Nature Science Foundation of China (61377023, 61422510, 91233056), Zhejiang Provincial Natural Science Foundation of China (LY13F050002), The Doctoral Fund of Ministry of Education of China (No. 20120101110094) and the Program of Zhejiang Leading Team of Science and Technology Innovation (2010R50007).

**Author Contributions:** Y. Shi, K. Ma and D. Dai conceived and performed the simulations and the design of the devices reported in the paper. Y. Shi and D. Dai contributed to the writing and organization of the contents.

**Conflicts of Interest:** The authors declare no conflict of interest.

**References**


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A Small Polymeric Ridge Waveguide With a High Index Contrast

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Abstract—In this paper, an optimal design of a small polymeric ridge waveguide with a high index contrast is presented. In order to reduce the leakage to the substrate and pure bending losses, the buffer layer of the present waveguide is etched partially. The single-mode condition, the bending characteristics, and the birefringence of the present small polymeric ridge waveguide are also studied. By adjusting the core width and the core height, it is possible to obtain a polarization-insensitive small polymer ridge waveguide. For the bending loss, the numerical results show that the dominant part is the transition loss between the straight and bending sections (other than the pure bending loss) and the transition loss could be reduced greatly by introducing a lateral offset. However, the transition loss is still too large to obtain a very small bending radius (e.g., 10 μm). When only the pure bending loss is necessary to consider in some special case (e.g., microrings without any transitions), one can have a bending radius less than 10 μm due to the possibility of low pure bending loss.

Index Terms—Bending, polarization, polymer, ridge, single mode.

I. INTRODUCTION

In recent years, much attention has been drawn on increasing the integration density of photonic integrated circuits (PIC) and realizing large scale optical integrations, which will bring the cost reduction through high-yield wafer-scale processes and the improvement of performances [1]. There are several kinds of popular solutions for realizing ultracompact PICs by using e.g., ultrahigh index contrast (Δ) waveguides [2], photonic crystal waveguides [3], and surface plasmon waveguides [4]. Among these solutions, the most flexible and simplest way is using a waveguide with an ultrahigh index contrast [5]. For example, Si nanowires have been one of the most attractive choices to realize ultrasmall photonic integrated devices recently [6]. However, for the fabrication of Si nanowires, one usually has to use some expensive lithography techniques (such as E-beam or deep-ultraviolet (UV) lithography [5]–[7]), and there is a serious problem for Si nanowires, i.e., the large scattering loss due to the surface roughness. Furthermore, since Si material is opaque in the visible range of light, Si nanowires are only available in the infrared range (>1200 nm), which is good for optical communication but not good for optical sensing in the visible range.

To overcome these drawbacks, an optical waveguide with an air-cladding and a low index core (e.g., SiO₂) is preferred. In this case, the core width is usually in the range of [1.0, 2.0] μm, which makes the fabrication easier (a regular lithography technique is good), e.g., the deeply etched SiO₂ ridge waveguide proposed in our previous paper [8]. However, for the deeply etched SiO₂ ridge waveguide, a very large aspect ratio is usually needed for a desirable ultrasharp bend due to the low index contrast Δ in the vertical direction [8]. In this paper, we present a minimized polymeric ridge waveguide, which has a polymeric core (e.g., commercialized SU-8 with a refractive index of about 1.57 [9]), a SiO₂ buffer layer (∼1.45), and an air cladding. For the present case, the vertical index contrast is relative large so that the large aspect ratio is avoided even for a small bending radius. According to the transparent range of SU-8, the present minimized polymeric waveguide is available not only in the infrared range (1550 nm) for optical communications but also in the visible range of light for other applications (e.g., optical sensing).

It is well known that a polarization-insensitive performance is often demanded for optical waveguide devices used in various applications such as optical fiber-communication system. However, in a minimized optical waveguide with a high Δ, the geometrical asymmetry usually introduces a large birefringence, which causes a large polarization dependency for optical devices. Chin et al. have theoretically explored a possibility of designing an intrinsically polarization-independent microring resonator by using a judicious combination of critical ridge width and etch depth based on InP materials [10]. In this paper, we use a finite-difference method (FDM) mode solver with perfect matched layers (PMLs) [11] for a detailed analysis on the characteristics of the present small polymeric waveguides, such as the single-mode condition, the bending loss, and the nonbirefringence design.

II. DESIGN AND SIMULATION

Fig. 1 shows the schematic configuration of the present small polymeric ridge waveguide, which has an etched-through polymeric core with a height of h(core) and a width of w(core), a SiO₂ buffer layer, and an air cladding. In our fabrication, we chose NANO™ SU-8 2005 negative tone photoresist from MicroChem Corporation (MCC, Newton, MA) as the material for the waveguide core. To achieve SU-8 films with different
film thicknesses (i.e., \( h_{\text{core}} \)), the material was diluted with cyclopentanone and spin-coated with different spin speed. The SiO\(_2\) buffer layer was deposited by Surface Technology Systems, plc. (STS, Imperial Park, Newport, U.K.) plasma enhanced chemical vapor deposition (PECVD) system. The refractive indices of the layers of SU-8 core and SiO\(_2\) buffer are \( n_{\text{core}} = 1.573 \) and \( n_{\text{buffer}} = 1.450 \), respectively, which were measured by using a Metricon 2010 prism coupler system. In order to achieve a high refractive index contrast and consequently a small bending radius, in the following design, we introduce the deep etching, i.e., a part of the SiO\(_2\) buffer layer is also etched to a depth of \( h_{\text{rib}} \) (see Fig. 1). One should note that the side wall of the polymer core may be damaged in some degree during the etching of silica buffer layer, e.g., introducing a relative large roughness at the sidewall of the polymeric core. Therefore, one should carefully choose the recipe for the inductively coupled plasma (ICP) dry etching (e.g., the flow ratio of reactive gases) or use chemical wet etching as an alternative.

Fig. 1 shows the singlemode condition for straight waveguides \((h_{\text{rib}} = 0, 1.0 \, \mu\text{m})\). First we consider the case with \( h_{\text{rib}} = 0 \) for the simplicity. The case of \( h_{\text{rib}} = 1.0 \, \mu\text{m} \) will be discussed later. For the determination of the singlemode condition, an FDM mode solver with PMLS is used to calculate the propagation constants and the field distributions of the quasi-TE (q-TE) or quasi-TM (q-TM) eigenmodes for the optical waveguides with different core widths \( w_{\text{core}} \) and core heights \( h_{\text{core}} \).

The single-mode (S-M) condition is determined by the cutoff boundary of the first higher order mode. In this paper, we use the condition \( L_{\text{dk}} > 30 \, \text{dB/cm} \) as the cutoff condition for the higher order mode, where \( L_{\text{dk}} \) is the leakage loss of the higher order mode. For the case with a relative small core height (e.g., \( h_{\text{core}} < 2.0 \, \mu\text{m} \) for q-TE mode), the first higher order mode is the mode \( E_{22}(x, y) \) (which has two peaks at the lateral direction and one peak at the vertical direction). When the core height becomes large, the mode \( E_{12}(x, y) \), which has one peak at the lateral direction and two peaks at the vertical direction, becomes the first higher order mode. As a result, the curves for S-M condition \((h_{\text{rib}} = 0)\) are broken into two separated curves near \( h_{\text{core}} = 2.0 \, \mu\text{m} \) and \( h_{\text{core}} = 2.2 \, \mu\text{m} \), respectively, for both q-TE and q-TM modes as shown in Fig. 2. Due to the geometrical asymmetry of the optical waveguide, the fundamental mode cuts off at a certain aspect when the effective refractive index \( n_{\text{eff}} \) is equal to the refractive index of the buffer layer. The cutoff boundaries for fundamental modes are also plotted by dashed lines in Fig. 2 for both q-TE and q-TM modes. When the point \((h_{\text{core}} \text{ and } w_{\text{core}})\) is below the boundaries, the \( n_{\text{eff}} \) of fundamental mode is underneath the refractive index of buffer layer, which indicates that no guided mode is supported in the waveguide.

From Fig. 2, one can easily choose the parameters for an S-M polymer waveguide. We also consider the design of a non-birefringent waveguide by choosing the geometrical parameters \((h_{\text{core}} \text{ and } w_{\text{core}})\). The birefringence \( B \) is defined as the difference between the effective indices of the q-TE and q-TM polarization modes. The relations between the height and width of the core for a polymer waveguide with \( B = 0, \pm 5 \times 10^{-4} \), are shown by dotted–dashed curve and dotted curves in Fig. 2. The polarization-insensitive region is defined by these curves of \( B = \pm 5 \times 10^{-4} \). When one chooses the parameters from the curve of \( B = 0 \), a nonbirefringent design is obtained. The tolerance for polarization insensitivity in the geometric structure is rather small as shown in Fig. 2 defined by the two curves of \( B = \pm 5 \times 10^{-4} \) near the curve of \( B = 0 \). Due to the small tolerance, it is not easy to fabricate a nonbirefringent waveguide, however, the simulation result is helpful to design an optical waveguide with relative small birefringence so that it is possible to compensate the residual birefringence by some postprocesses.

In Fig. 2, an S-M and polarization-insensitive straight waveguide could be designed from the solid and dashed lines in the S-M region. The small size and the strong confinement of the present waveguide are beneficial to realize high integration density. From Fig. 2, we choose \( h_{\text{core}} = 1.4 \, \mu\text{m} \) and \( w_{\text{core}} = 1.934 \, \mu\text{m} \) to have a polarization-insensitive S-M waveguide in the following design and simulation.

In order to increase the integration density of PICs, a small bending radius is desirable. In our case, the bending loss of the present polymeric waveguide is calculated from the propagation constant and the field distribution of the eigenmode obtained by using an FDM mode solver with a PML boundary condition. Fig. 3 shows the calculated pure bending losses for differ-
different bending radii $R$ as the etched depth $h_{\text{rib}}$ increases. Since the bending characteristics of the q-TM and q-TE fundamental modes are similar, only the results for q-TE mode are shown in Fig. 3.

Fig. 3 shows that the pure bending loss increases as the bending radius decreased. When the buffer layer is not etched (i.e., $h_{\text{rib}} = 0$), the bending waveguide with a small bending radius $R \leq 30 \, \mu m$ experiences very large pure bending losses. One has to increase the bending radius to a larger value (like 75 \, \mu m) to obtain a low bending loss ($< 0.1 \, \text{dB/90}^\circ$). From Fig. 3, one sees that it is possible to reduce the pure bending loss greatly by etching down the buffer layer. For example, when the etched depth $h_{\text{rib}} > 2.0 \, \mu m$, one obtains a bending loss as low as 0.01 \, dB/90° even for an extremely small bending radius $R = 5 \, \mu m$.

From Fig. 3, we also note that the bending loss becomes almost unchanged when the etching depth increases further. Moreover, a deep etching will usually introduce a relative large roughness of the waveguide sidewall. Therefore, it is not necessary to have a too large etching depth for the buffer layer (no more than 2.0 \, \mu m for the case of $R = 5 \, \mu m$).

On the other hand, etching the buffer layer will also reduce the losses of the higher order modes. Therefore, the S-M condition for the waveguide with an etched buffer will be more critical than the case of $h_{\text{rib}} = 0$, which indicates the single-mode/multimode boundary will be lowered a little. In order to avoid the multimode behavior, the cross section of the waveguide should be scaled down. Therefore, one should check the S-M condition again after choosing the etched depth. In our design, in order to ensure a low bending loss ($< 0.1 \, \text{dB/90}^\circ$) for a bending radius of $R > 10 \, \mu m$, we choose the etching depth $h_{\text{rib}} = 1.0 \, \mu m$. The corresponding S-M condition was shown in Fig. 2 previously. In this case, the S-M condition becomes different from the case of $h_{\text{rib}} = 0$, particularly that for q-TM mode. For the case of $h_{\text{rib}} = 1.0 \, \mu m$, when $h_{\text{core}}$ increases from a small value to the large one, the first higher order mode for q-TM mode is always $E_{21}(x,y)$ and thus the curve is not broken into two parts (which is very different from that for the case $h_{\text{rib}} = 0$). Etching the buffer layer will also influence the polarization insensitive condition, which should be taken into considerations while designing.

We note that a bending waveguide has a different birefringence from a straight one, which means that an optical waveguide with zero birefringence in straight section may suffer large birefringence while being bent. This bending-induced birefringence can be diminished by choosing an optimal core width for the bending section individually (not the same as that for the straight section). Fig. 4 shows the optimal core width $w_{\text{core}}$ for nonbirefringent bending waveguide as a function of the bending radius $R$. Here, the etched depth of the buffer layers $h_{\text{rib}} = 1 \, \mu m$ and the results for two cases ($h_{\text{core}} = 1.4 \, \mu m$ and $h_{\text{core}} = 1.5 \, \mu m$) are shown. From the numerical simulation, we obtain a fitting function $W = a \cdot \exp[b/(R-c)] + d$ to estimate the optimal width, where $a$, $b$, $c$, and $d$ are constants. The dashed lines in Fig. 4 illustrate the optimal $w_{\text{core}}$ for the nonbirefringent straight waveguides. From Fig. 4, one sees that when the bending radius is large (e.g., $R > 200 \, \mu m$) the optimal width $w_{\text{core}}$ is insensitive to the bending radius and almost the same as that of a straight waveguide. The optimal width $w_{\text{core}}$ increases rapidly when the bending radius decreases below 50 \, \mu m. For example, the optimal width $w_{\text{core}}$ becomes as large as 2.3 \, \mu m when $R = 30 \, \mu m$. From Fig. 4, for a very small bending radius (e.g., 10 \, \mu m), it is almost impossible to achieve a nonbirefringent bending by simply adjusting its core width.

Besides the pure bending loss, we also need to consider the transition loss, which results from the mismatch of the fields at the junction of the bending and straight sections. The transition loss is usually estimated by using an overlapping integral method [12], and it can be reduced by introducing a lateral offset $b$ between the bending and straight sections [13]. Fig. 5 shows the calculated transition losses of both q-TE and q-TM modes for different bending radii when $h_{\text{core}} = 1.4 \, \mu m$ and $h_{\text{rib}} = 1.0 \, \mu m$. The core width of the straight waveguide is chosen as $w_{\text{core}} = 1.962 \, \mu m$ to make it polarization insensitive. For any given bending radius, we choose the corresponding optimal core widths $w_{\text{core}}$ according to Fig. 4. Form Fig. 5, one sees that when the bending radius increases, the transition loss gets smaller as expected. According to Fig. 5, the optimal offset for

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**Fig. 3.** Bending loss as the etched depth $h_{\text{rib}}$ increasing ($h_{\text{core}} = 1.4 \, \mu m$ and $w_{\text{core}} = 1.934 \, \mu m$).

**Fig. 4.** Optimal width $w_{\text{core}}$ for a nonbirefringent bending waveguide with a given core height as the bending radius $R$ varies.
a minimized transition loss is polarization sensitive. Thus, one should choose the offset $\delta$ carefully to minimize the transition losses for both q-TE and TM modes. Here we choose the offset value at the intersection point (see the points in Fig. 5).

In order to achieve compact design for photonic integrated devices, a small bending radius is always desirable. For the present minimized polymeric optical waveguide, the minimal bending radius is about several tens of microns for a small total loss (the sum of the pure bending loss and the transition loss). We note that the total loss mainly comes from the transition loss at the junctions. Therefore, if the number of junctions can be reduced, it is possible to achieve a very small bending radius with low total bending loss. For example, for microring resonators (MRRs), there is no straight and bending junction and thus the total size of an MRR based on the present optical waveguide could have a compact size.

Besides the minimal bending radius, the gap width $G$ between two adjacent waveguides is also a key factor to determine the density of photonic circuits [14]. For the present waveguides with high $\Delta$, two adjacent waveguides can be placed very close due to the weak coupling between them. For example, for two identical parallel straight waveguides ($h_{\text{core}} = 1.4 \, \mu m$, $w_{\text{core}} = 1.934 \, \mu m$, $h_{\text{rib}} = 0$), less than 0.05% of the power in the input waveguide is coupled into the other waveguide after propagating a distance of 1 cm when the gap width $G > 3 \, \mu m$.

III. CONCLUSION

In this paper, a nonbirefringent polymeric ridge waveguide with high $\Delta$ has been introduced. First, the S-M condition has been given in details from the modal analyses based on the FDM mode solving. By adjusting the aspect ratio, the design for nonbirefringent optical waveguides has been obtained. The bending loss (including the pure bending loss and the transition loss) of the present optical waveguide has been analyzed. Since the birefringence is sensitive to the bending radius, we have chosen different optimal core widths for the straight and bending sections to be nonbirefringent. In order to achieve a small bending radius with low bending loss, the buffer layer with a certain etched depth is introduced. In this case, the pure bending loss is very small and the transition loss becomes dominant. In our design, a lateral offset has been introduced and the transition loss has been reduced greatly. With such a design, a relative small bending radius of several tens of microns has been obtained for a nonbirefringent optical waveguide. On the other hand, it is possible to reduce the bending radius to less than 10 $\mu m$ for a structure without transitions (such as microring resonators).

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Dr. He is a Fellow of the Optical Society of America (OSA).
Fabrication and Characterization of Small Optical Ridge Waveguides Based on SU-8 Polymer

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Abstract—Small SU-8 ridge optical waveguides with an air cladding and a SiO$_2$ buffer on Si substrate have been realized by using a direct ultraviolet (UV) photolithography technology. The propagation loss measured by the cut-back method is about 0.1 dB/mm (@1550 nm) when the core width is 2.8 µm. The bending losses of the present SU-8 optical ridge waveguides are also characterized. The measured results show that the bending loss decreases exponentially as the bending radius increases and the total loss can be reduced effectively by introducing an appropriate offset between two connected sections with different curvatures. A small bending radius (as small as 75 µm) is still allowed for the requirement of a small bending loss (< 0.1 dB) when an offset of 0.1 µm is introduced. Finally, by using this kind of waveguide, a small 1 × 2 Y-branch power splitter is fabricated and characterized.

Index Terms—Bending loss, polymer, propagation loss, ridge waveguide, SU-8, Y-branch.

I. INTRODUCTION

As widely known, LiNbO$_3$, silica, silicon, III-V semiconductor, and polymers are the most popular materials for photonic integrated circuits (PICs). Among them, polymeric materials possess the advantages of highly flexibility, low cost and easy fabrication process [1]–[3]. Besides, polymer usually has a large transparent window [2], and a relatively wide range of refractive index (which could be changed through the synthesis processing and heat treatments [5]). There are mainly two types of polymeric materials [2]. One is nonphotosensitive (such as most polyimides and polycarbonates) and consequently a reactive-ion-etching process for patterning is needed. The other one is photosensitive (e.g., SU-8 polymer) and consequently only a UV photolithography is needed. In this way, the fabrication becomes very simple and convenient [3], [4].

SU-8 polymer is a negative epoxy based photoresist developed by IBM for micromachining and other microelectronic applications in early 1990s [6], [7]. One of its numerous advantages is that a wide range of film thickness from 0.75 µm to 450 µm can be achieved with a conventional spin coating process. Besides, SU-8 has very high transmission for the wavelength range above 400 nm [4] and exhibits relatively good chemical and thermal stabilities (with a glass transition temperature of $T_g$ ≈ 200 °C, and a degradation temperature of $T_d$ ≈ 380 °C) [7]. Therefore, SU-8 is an attractive polymer material for PICs used in telecommunication and sensing. In the past years, various PICs with buried SU-8 waveguides have been demonstrated, e.g., Y-branch power splitters [4], micro-ring filters/modulators [8], and arrayed waveguide grating (AWG) [9]. In the previous work, people have achieved low-loss buried SU-8 waveguides at various wavelengths, e.g., 0.019 dB/mm @ 632.8 nm [10], 0.036 dB/mm @ 830 nm [3], 0.077 dB/mm @ 1310 nm [4], and 0.125 dB/mm @ 1550 nm [4]. Because of the large core size, the buried SU-8 waveguides normally have a high coupling efficiency with single mode fibers. However, a large bending radius is inevitable for the buried optical waveguides due to the low refractive index contrasts. This is not good for achieving a high integration density. Therefore, it is necessary to develop small optical waveguides with higher index contrasts, e.g., by introducing an air over-cladding (rather than the buried type). Consequently, a smaller bending radius is allowable. People have developed air-cladded SU-8 ridge waveguides for the wavelength of 980 nm, and the corresponding propagation loss are 0.136 dB/mm and 0.201 dB/mm for TE mode and TM mode, respectively [11]. For the wavelength of 1550 nm, a relatively low propagation loss of 0.3 dB/mm was obtained [12]. Such air-cladded waveguide structures have been applied for optical sensing [13], [14] because of their advantages of small size and high sensitivity.

In this paper, we present small ridge optical waveguides based on the SU-8 2000 polymer from Microchem Corporation. Both the propagation loss of straight waveguides and the bending loss are measured at 1550 nm. A compact 1 × 2 Y-branch power splitter is also demonstrated as an example.

II. STRUCTURE AND FABRICATION

In this paper, we choose SU-8 2000 (from Microchem Corporation) as the core material. In order to obtain a strong confinement of light to reduce the bending radius, we use a ridge waveguide with an air cladding and a SiO$_2$ insulator on Si substrate, as shown in Fig. 1. The guiding properties of this structure, such as single mode condition and bending loss, have been investigated numerically in our previous work [15]. The inset in the left-top corner of Fig. 1 shows the calculated fundamental mode (TM$_{00}$) of a 2.0 µm-wide and 1.7 µm-high optical waveguide (@ 1550 nm), which is chosen for our S-bends and Y-branch splitter (in Section III). The refractive indices of SU-8 and SiO$_2$...
are 1.574 and 1.455, respectively. The mode profile slightly deviates from the core center in the vertical direction because of the asymmetry of the SiO₂ buffer layer and the air-cladding.

Because of the photosensitivity of SU-8 2000, only a direct UV-photolithography is needed, which greatly simplifies the fabrication process [4]. For the fabrication, firstly a 5 μm-thick SiO₂ insulator layer is deposited on a cleaned Si substrate by plasma-enhanced chemical vapor deposition (PECVD) system. The 5 μm-thick SiO₂ layer is thick enough to avoid light leakage towards the Si substrate. The SU-8 polymer film is then formed on the SiO₂ buffer layer by a spin-coating process. One can obtain SU-8 films with different thicknesses by controlling the dilute concentration and the spinning speed [6]. In our experiment, we have gotten the film thickness of about 1.7 μm by diluting SU-8 with the cyclopentanone of the same volume and using the spinning speed of 2500 rpm. The Si-wafer with the SU-8 core layer is then prebaked (1 h @ 65 °C and 2 h @ 95 °C) to evaporate the solvent. Then, by using the direct I-line UV photolithography, the patterns on the photo-mask are transferred to the SU-8 film. A 2-h postbaking (i.e., 1 h @ 65 °C and 1 h @ 95 °C) is necessary to make the exposed SU-8 cross linked sufficiently. Then a development process follows, in which the unexposed part of SU-8 polymer is removed. The remaining part is for the core of the ridge optical waveguide. Then the wafer is rinsed in ethanol solvent and then in DI water, and dried by nitrogen blowing. Like ethanol, iso-propanol can also be adopted, which offers similar results. Finally, a 30-min hard-bake (@ 120 °C) is carried out to get stable SU-8 2000 properties.

Fig. 2 shows a SEM (scanning electron microscope) picture for the cleaved facet of the fabricated straight waveguide. From this figure, one sees that the SU-8 ridge optical waveguide has relatively vertical and smooth sidewalls, which is beneficial to obtain a low propagation loss. The round corners on the top of the fabricated waveguide (see Fig. 2) are mainly induced by the long postbaking time, which is helpful to smoothen the waveguide sidewalls and consequently reduce the scattering loss. On the other hand, in order to have square waveguides, a shorter baking time is preferred [5]. However, it may lead to a bad adhesion of the SU-8 thin film to the SiO₂ buffer layer. Therefore, the baking time should be optimized further to fabricate SU-8 waveguides with improved performances, in our future work. The inset in the right-top corner of Fig. 2 shows the mode profile captured by using a CCD (charge-coupled device) camera. This mode profile indicates a singlemode propagation in the fabricated SU-8 ridge waveguide.

III. CHARACTERIZATION

For the characterization of both straight waveguides and S-bend series, we use a semiconductor laser diode (SLD) as the light source in our measurement system. The SLD has a central wavelength of 1550 nm. An in-line fiber polarizer is used to obtain a polarized input light, which is butt-coupled to the fabricated optical waveguide through a polarization maintaining fiber (PMF). The PMF is fixed on a fiber rotator so that it is easy to achieve TE- or TM-polarized light by rotating the PMF. In order to improve the coupling efficiency, a tapered lens fiber (TLF) is used to collect the output light from the output end of the optical waveguide. The TLF is connected to an optical power meter.

We have fabricated a series of straight waveguides with different core widths, namely, \( w_{\text{core}} = 1.2 \, \mu \text{m}, 1.6 \, \mu \text{m}, 2.0 \, \mu \text{m}, 2.4 \, \mu \text{m}, \text{and } 2.8 \, \mu \text{m} \). Propagation loss was measured by the cut-back method for both TE- and TM-polarizations. Here we measured the insertion losses of all the straight waveguides with different lengths (\( L = 37.5 \, \text{mm}, 27.5 \, \text{mm}, \text{and } 10.5 \, \text{mm} \)). For any core width \( w_{\text{core}} \), the relationship between the insertion loss (dB) and the waveguide length \( L \) was fitted with a linear function and the slope of the fitting line indicates the propagation loss in decibels (dB) per unit length. Table I shows the measured propagation losses \( L_{\text{prop, p-TM}} \) for TE polarization and the polarization dependent losses (PDL) of the small SU-8 ridge waveguides with different core widths. From Table I, one sees that the propagation loss will be smaller when the waveguide core becomes wider. For example, when \( w_{\text{core}} \) is chosen as 2.8 μm and 1.2 μm, the propagation losses are 0.14 dB/mm and 0.24 dB/mm, respectively. This is due to the larger field amplitude at the sidewalls when the core width is smaller [17]. For the waveguide with a fixed core width, the propagation loss for TM-polarized light (\( L_{\text{prop, p-TM}} \)) is a little larger than that for TE-polarized light (\( L_{\text{prop, p-TE}} \)), and the difference (i.e., PDL = \( L_{\text{prop, p-TM}} - L_{\text{prop, p-TE}} \)) is given in Table I. For SU-8 polymer, the material birefringence obtained by the prism coupling method is as low as \( 1 \sim 2 \times 10^{-4} \), which is comparable to that of halogenated acrylate polymers [4]. In comparison with this relatively small material birefringence, the birefringence due to the geometrical asymmetry may be dominant, which should be considered when designing a polarization-insensitive photonic devices (e.g., arrayed waveguide gratings, microring resonators). It is possible to achieve nonbirefringent optical waveguides by choosing appropriate structural parameters [15]. Due to the field distributions for TE and TM polarizations are different slightly, the scattering losses due to the sidewall roughness are a little polarization-dependent. Fortunately, the polarization-dependent loss
is small for our fabricated waveguides (see Table I). The coupling loss between the PMF and the waveguide is ∼ 8 dB/facet at the input port. For the output port, the coupling efficiency is about 50% due to the use of the TLF with a much smaller spot size.

Bent waveguides are essential elements for PICs. In order to have compact PICs, it is desirable to choose a small bending radius. On the other hand, it is important to ensure an acceptably low bending loss by choosing a large bending radius. It is well known that the bending loss includes the pure bending loss and the transition loss [18]. The transition loss is due to the mode mismatch at the junction between the sections with different curvature radii. An effective method to reduce the transition loss is introducing a lateral offset at the junctions [19]. In this paper, we designed and fabricated a series of S-bends with different bending radii R and different lateral offsets δ. Each S-bend consists of two connected 90°-arc waveguides with the same bending radius. In our design, we consider the S-bends with the bending radii R = 300 μm, 200 μm, 150 μm, 100 μm, 75 μm, 50 μm and 25 μm. Three different offsets δ = 0, 0.05, and 0.1 μm are included for the bending radii R ≤ 100 μm.

Fig. 3(a) shows the SEM picture of the fabricated SU-8 S-bend patterns with R = 25 μm and Fig. 3(b) shows the enlarged view for the part defined by the dashed rectangle in Fig. 3(a). The small offsets (i.e., δ ≤ 0.1 μm) are quite difficult to be distinguished from SEM pictures, e.g., δ = 0.05 μm in Fig. 3(b), because they are very small in comparison with the core width of ∼ 2.0 μm. Furthermore, due to the light diffraction during the photolithograph process, the offset junction is rounded. Consequently, usually it is not easy to observe a sharp offset junction. When using improved fabrication processes (e.g., with a high resolution), one may see a sharp offset through SEM pictures.

By using our measurement system, we obtained the output power for each S-bend series. In our experiment, we consider the case of core width w_{core} = 2.0 μm, which satisfies the single mode condition [15]. The obtained output power P as the number N of 90°-bend increases for the case of R = 50 μm is shown in Fig. 4(a) as an example. The power shown in Fig. 4(a) is normalized with respect to the output power of a straight waveguide so that the butt-coupling loss between the input/output fiber and the ridge waveguide is cancelled. Here the measured data for the cases of δ = 0, 0.05, and 0.1 μm are shown by triangles, squares and diamonds, respectively. From this figure, one sees that for a given bending radius R the normalized power P decreases almost linearly as the number N of 90°-bend increases.

In order to obtain the bending losses, we use a linear function to fit the relation between the measured power P and the 90°-bend number N. The slope of the fitting line gives the total bending loss per 90°-bend (including the pure bending loss and the transition loss). From Fig. 4(a), we obtain the total bending losses per 90°-bend for the cases of δ = 0, 0.05, and 0.1 μm, which are shown by triangles, squares and diamonds.

**TABLE I**

<table>
<thead>
<tr>
<th>w_{core} (μm)</th>
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<td>0.17</td>
<td>0.15</td>
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<td>PDL (dB/mm)</td>
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<td>0.03</td>
<td>0.04</td>
<td>0.06</td>
</tr>
</tbody>
</table>

**Fig. 3.** (a) SEM image of S-bends with R = 25 μm; (b) An enlarged view of the part defined by the dashed rectangle in (a).

**Fig. 4.** (a) Normalized power P as the number N of 90°-bend increases when R = 50 μm; (b) total bending loss per 90°-bend as the bending radius R increases when the offset δ = 0, 0.05, and 0.1 μm.
in Fig. 4(b), respectively. In this figure, we also give the fitted curves for the three cases.

From Fig. 4(b), one can see that when the bending radius $R$ increases, the total bending loss per 90°-bend decays exponentially as predicted. For example, for the case of $\delta = 0$, the bending loss decreases quickly from 0.97 dB to 0.13 dB when $R$ increases from 25 $\mu$m to 100 $\mu$m. On the other hand, for a larger bending radius, the length (i.e., $R\pi/2$) of a single 90°-bend increases and consequently a larger scattering loss is introduced. Therefore, there is no notable reduction of bending loss when the bending radius increases further. For example, when $R = 200$ and 300 $\mu$m (with $\delta = 0$), the total bending loss per 90°-bend measured in our experiments are about 0.12 and 0.2 dB. As mentioned above, introducing a lateral offset at the junctions is an effective method to reduce the transition loss. From Fig. 4(b), one sees for the case of $R = 75$ $\mu$m, the bending loss (0.256 dB @ $\delta = 0$) is reduced to 0.168 dB and 0.09 dB when introducing an offset of $\delta = 0.05$ $\mu$m and 0.1 $\mu$m, respectively. Therefore, when a bending loss of 0.1 dB for a 90°-bend is allowable, the minimal bending radius can be as small as 75 $\mu$m by introducing an offset of 0.1 $\mu$m. For the present SU-8 ridge waveguide, there is a high index contrast at the lateral direction. However, at the vertical direction, the index contrast between SU-8 core and the SiO$_2$ buffer is relatively low. For a very small bending radius, the leakage to the buffer layer and substrate becomes significant. This prevents the further reduction of the bending radius. Therefore, when very small bending radius is desirable, it is necessary to enhance the confinement at the vertical direction. For example, by etching the SiO$_2$ buffer partially, it is possible to reduce the bending radius to 10 $\mu$m [15]. Another method for reducing the bending area is using 90°-corner bends [16]. However, the facet for the corner mirror is usually required to be very critical and smooth to achieve a low-loss turning loss (like [16]). This makes the fabrication more critical in comparison with that for the regular 90°-arc bends.

By using the present small ridge waveguide which allows a small bending radius, we have realized a small 1 $\times$ 2 Y-branch power splitter. Fig. 5 shows the SEM image of the designed and fabricated 1 $\times$ 2 power splitter. The Y-branch power splitter consists of an input waveguide with a cross section of 2.0 $\times$ 1.7 $\mu$m$^2$ and two S-bend output waveguides (branch #1, branch #2) with the same cross section size. The S-bend for the output waveguide has a bending radius of 200 $\mu$m to guarantee a low bending loss. Here we do not introduce offset for the S-bend. Due to the limitation of resolution of the UV lithography technique, the pattern at the sharp angle at the junction (see the inset in Fig. 5) was not formed ideally. This will introduce some excess loss due to the scattering at the junction (see Fig. 6). Fig. 6 shows the measured spectral responses of the output ports, which are normalized by the transmission loss of a straight waveguide with the same length. The two curves represent the normalized power from branch #1 and branch #2, respectively. The wavelength ranges from 1450 nm to 1650 nm, which is limited by the bandwidth of the SLD source. From Fig. 6, one sees that the uniformity of this compact power splitter is good. The relatively large excess loss is mainly due to the scattering loss at the junction. There is a loss fluctuation of about 2.5 dB around 1510 nm in the optical spectrums (see Fig. 6), which may be due to some multimode effects. It is possible to obtain compact photonic integrated devices with better performances and more complex structures by improving the design and the fabrication process in the future work. Furthermore, because of the air-cladding, the present SU-8 ridge waveguide should be attractive to realize low-cost and compact photonic integrated devices for optical sensing.

![Fig. 5. SEM picture of the present compact 1 $\times$ 2 Y-branch power splitter (the inset shows an enlarged view of the junction).](image)

**Fig. 5.** SEM picture of the present compact 1 $\times$ 2 Y-branch power splitter (the inset shows an enlarged view of the junction).

**Fig. 6.** Measured optical spectral responses of branch #1 and branch #2.

**IV. CONCLUSION**

In summary, we have fabricated small optical ridge waveguides based on SU-8 polymer by using direct UV-lithography technology. The propagation loss measured by using the cutback method is about 0.14 dB/mm (@ 1550 nm) when the core width $w_{core} = 2.8$ $\mu$m. When the core width decreases, the propagation loss increases. Bending losses of the present small optical ridge waveguides (with core width $w_{core} = 2.0$ $\mu$m) have been also characterized. When the bending radius increases, the measured bending loss decreases exponentially as predicted. For example, for the case of $\delta = 0$, the bending loss decreases quickly from 0.97 dB to 0.13 dB when $R$ increases from 25 $\mu$m to 100 $\mu$m. Our experimental results have also shown that the transition loss has been reduced greatly by introducing a lateral offset for the S-bend. Due to the limitation of resolution of the UV lithography technique, the pattern at the sharp angle at the junction (see the inset in Fig. 5) was not formed ideally. This will introduce some excess loss due to the scattering at the junction (see Fig. 6). Fig. 6 shows the measured spectral responses of the output ports, which are normalized by the transmission loss of a straight waveguide with the same length. The two curves represent the normalized power from branch #1 and branch #2, respectively. The wavelength ranges from 1450 nm to 1650 nm, which is limited by the bandwidth of the SLD source. From Fig. 6, one sees that the uniformity of this compact power splitter is good. The relatively large excess loss is mainly due to the scattering loss at the junction. There is a loss fluctuation of about 2.5 dB around 1510 nm in the optical spectrums (see Fig. 6), which may be due to some multimode effects. It is possible to obtain compact photonic integrated devices with better performances and more complex structures by improving the design and the fabrication process in the future work. Furthermore, because of the air-cladding, the present SU-8 ridge waveguide should be attractive to realize low-cost and compact photonic integrated devices for optical sensing.

In summary, we have fabricated small optical ridge waveguides based on SU-8 polymer by using direct UV-lithography technology. The propagation loss measured by using the cutback method is about 0.14 dB/mm (@ 1550 nm) when the core width $w_{core} = 2.8$ $\mu$m. When the core width decreases, the propagation loss increases. Bending losses of the present small optical ridge waveguides (with core width $w_{core} = 2.0$ $\mu$m) have been also characterized. When the bending radius increases, the measured bending loss decreases exponentially as predicted. For example, for the case of $\delta = 0$, the bending loss decreases quickly from 0.97 dB to 0.13 dB when $R$ increases from 25 $\mu$m to 100 $\mu$m. Our experimental results have also shown that the transition loss has been reduced greatly by introducing a lateral
offset at the junctions. With the requirement of 0.1 dB/90°-bend, the minimal bending radius for the present SU-8 optical waveguide is as small as $R = 75 \mu m$ when an offset of 0.1 \( \mu m \) is introduced. Usually, it is desirable to make the bending radius as small as possible in order to improve the integration density. For the present SU-8 ridge waveguide, the relatively low index contrast at the vertical direction (between SU-8 core and the SiO\(_2\) buffer) prevents the further reduction of the bending radius due to the leakage to the buffer/substrate. In order to enhance very small bending radius, it is necessary to enhance the confinement at the vertical direction, e.g., by etching the SiO\(_2\) buffer partially or using 90°-corner bends [16].

A 1 × 2 Y-branch power splitter has also been demonstrated with uniform power splitting for a broad wavelength band (> 200 nm). In this paper, our design and characterization have been focused for the wavelength range around 1550 nm. On the other hand, it has been demonstrated in [5] that SU-8 buried waveguides have a lower propagation loss at 1310 nm than that at 1550 nm. Therefore, it is expected that the present small SU-8 optical ridge waveguide will have better performances (especially low losses) when one chooses the operation wavelength as 1310 nm. Therefore, the present small optical ridge waveguide based on SU-8 polymer appears as a promising candidate for realizing easy-fabricated and low-loss integrated optical devices (especially for optical sensing) in a large wavelength range.

REFERENCES


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A silicon-based hybrid plasmonic waveguide with a metal cap for a nano-scale light confinement

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Abstract: A hybrid plasmonic waveguide with a metal cap on a silicon-on-insulator rib (or slab) is presented. There is a low-index material nano-layer between the Si layer and the metal layer. The field enhancement in the nano-layer provides a nano-scale confinement of the optical field (e.g., 50nm × 5nm) when operates at the optical wavelength λ = 1550nm. The theoretical investigation also shows that the present hybrid plasmonic waveguide has a low loss and consequently a relatively long propagation distance (on the order of several tens of λ).

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OCIS codes: (240.6680) Surface plasmons; (250.5300) Photonic integrated circuits; (130.2790) Guided waves

References and links

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1. Introduction

In order to have high-integration density, it is essential to develop a nano-scale optical waveguide which is the basic element for photonic integration circuits. Currently there are three kinds of popular nano-scale waveguides, namely, silicon-on-insulator (SOI) nanowires with an ultra-high index-contrast [1,2], photonic crystals [3], and surface plasmon (SP) waveguides [4–16]. For the former two nano-scale waveguides, the optical field confinement is limited to the order of a wavelength in each direction. In contrast, surface plasmon (SP) waveguides could provide a true nano-scale waveguiding and confinement of light. In the past years people have presented several three-dimensional structures which can support highly localized fields, e.g. narrow gaps between two metal interfaces [8–10,15,16] and V-grooves in metals [11,12]. However, it is well known that such a nano-scale optical waveguide has a large loss and the propagation distance is usually at the scale of several micrometers. Recently, a hybrid plasmonic waveguide with a dielectric cylinder above a metal surface has been presented for subwavelength confinement and long propagation distance [17]. However, it is not easy to fabricate such a waveguide structure due to the cylindrical structure. A rectangular plasmonic waveguide should be more attractive because it is possible to fabricate by using the standard planar lightwave circuit technology. In Ref [18], the authors has given an analyses for the dispersion relation and loss of subwavelength confined mode of several metal-GaAs-gap waveguides, e.g., a GaAs-cylinder with a gap of SiO2 on metal, a rectangular GaAs strip above Ag-substrate, and an Ag-gap-GaAs strip on a SiO2 substrate.

It is well known that recently silicon photonics has become very attractive because its fabrication compatibility to the standard CMOS microelectronics technology. It will be therefore interesting to develop a silicon-based hybrid plasmonic waveguide with simplified fabrication processes. In our previous paper, we have presented a SOI nanowire with a metal cap which is for a submicron-heater [19]. In that case, the SiO2 layer between silicon core and the metal cap is thick enough to prevent the absorption due to the metal. Here we consider the case when the SiO2 layer is very thin (e.g., several tens of nanometers). For such a SOI rib with a metal cap, when we consider the quasi-TM polarization (whose electrical field is vertical), there will be a field enhancement at the thin-SiO2 region due to the boundary condition of the electrical field, which is some similar to the horizontal slot waveguides [20]. Particularly, when the Si rib height is zero, one obtains a hybrid plasmonic waveguide with a Si slab and the etching depth is much shallown, which makes the fabrication much easier. The present hybrid plasmonic waveguide is also good to realize a low-voltage compact optical modulator when the nano-layer material between the Si layer and the metal layer has a high electro-optical coefficient. In this paper, we give a theoretical investigation on the modal characteristics of such a Si-based hybrid plasmonic waveguide.

2. Waveguide Structure and Analysis

Figure 1 shows the cross section of the present structure, which consists of a SOI rib with a metal cap. For such a structure, the fabrication is simple and CMOS compatible. One could use a standard SOI wafer. An alternative way is using the method of depositing SiO2 and
alpha-Si thin films on a Si substrate with the PECVD (plasma enhanced chemical vapor deposition) technology [21]. The next step is to form a SiO$_2$ thin film with a thickness of several tens of nanometers by using the PECVD technology or the process of thermal oxidation. By slowing down the speed of deposition or oxidation, it is possible to control the thickness precisely. Then a metal film (e.g., Ag or gold) is deposited on the SiO$_2$ layer. The photoresist thin film is then formed on the metal layer and the waveguide patterns are then defined by using E-beam lithography to have a high resolution. An RIE (Reactive Ion Etching) process is then used to etch through the layers of metal, SiO$_2$ (as shown in Fig. 1). The Si layer could be etched through or partially, which will be discussed below. For the fabrication, the metal cap is used as the mask for etching. More importantly, for the present structure, the metal cap contributes to the nano-scale waveguiding and confinement.

When the thickness of the SiO$_2$ layer between Si and metal is large (e.g., 0.5 μm), the fundamental mode field is confined well in the Si region and the metal layer almost does not influence the mode field distribution. In this case, the present structure is like a regular SOI nanowire. However, when the SiO$_2$ thickness becomes smaller (e.g., <50 nm), the metal layer will introduce a significant influence on the field distribution of the guided mode. As an example, we choose the geometrical dimensions as follows: $w_{co} = 200$ nm, $h_m = 100$ nm, $h_{SiO2} = 50$ nm, and $h_{Si_{rib}} = h_{Si} = 300$ nm. We choose the wavelength $\lambda = 1550$ nm and the corresponding refractive indices for all the involved materials as $n_{metal} = 0.1453 + 11.3587i$ (Ag) [17], $n_{SiO2} = 1.445$, and $n_{Si} = 3.455$. Here we consider an intrinsic Si layer which has a negligible material loss at the window around 1550 nm. When a doped Si layer is necessary for some special situations (e.g., when P-/N- contact is introduced), the loss due to the doping could be estimated by using the formula given in Ref [22]. For example, when the doping density $N = 10^{19}$/cm$^3$, the imaginary part of the refractive index $n_{im} = 0.2097$, which should be included when estimating the loss of the waveguide. For the case with an intrinsic Si layer (which is usually used for passive optical components), Fig. 2 shows the field distribution of the major-component $E_y(x, y)$ for the quasi-TM fundamental mode calculated by using an FEM (finite element method)-based mode solver. In order to see the profile more clearly, we also plot the field profiles $E_y(x, 0)$ and $E_y(0, y)$.

From the curve of $E_y(0, y)$, one sees that the field at 50nm-SiO$_2$ nano-layer is enhanced greatly. It is well known that there is a similar field enhancement in a low-index region in a pure-dielectric horizontal slot waveguide because of the strong discontinuity of the normal component of the electric field at the high-index-contrast interface [2,20]. For the present hybrid plasmonic waveguide, the principle is different partially. At the Si-SiO$_2$ interface, there is a strong discontinuity of the normal component of the electric field, which is the same as that in a pure-dielectric horizontal slot waveguide. On the other hand, at the SiO$_2$-metal interface, surface plasmon (SP) wave is excited. The electrical field of the excited SP wave decays exponentially at both sides of the interface and has a peak at the interface. In the thin
SiO$_2$ layer, the field distribution could be regarded as the sum of two exponential functions. When the SiO$_2$ layer is very thin (smaller than the evanescent penetration depth), the field at SiO$_2$ layer is enhanced greatly, as shown in Fig. 2. In the following parts, we consider the designs with different thicknesses of SiO$_2$ ($h_{SiO2} = 50$ nm, 20 nm, or 5 nm) and the other parameters are chosen as $h_{m} = 100$ nm and $h_{Si} = 300$ nm.

First we consider the case of $h_{Si_{rib}} = H_{Si} = 300$ nm (i.e., the Si layer is etched through). Figure 3 (a) shows the real part of the effective refractive index of the present hybrid optical waveguide with different SiO$_2$ nano-layer thicknesses as the core width $w_{co}$ decreases. For the case with a thinner SiO$_2$ layer, the effective index $n_{eff}$ becomes larger. When the core width decreases, the effective index decreases. Even when the core width decreases to 50 nm, there is still a guided mode supported in the hybrid optical waveguide, which is very interesting to have nano-scale light confinement (similar to the other metal waveguides). On the other hand, for the realization of plasmonic waveguide devices, it is very important to allow a long propagation distance, $L_{prop}$, which is defined as the distance that the amplitude of the field attenuates to $1/e$, i.e., $L_{prop} = 1/(n_{im}k_0)$ where $n_{im}$ is imaginary part of the effective refractive index $n_{eff}$. $k_0$ is the wave number in vacuum ($k_0 = 2\pi/\lambda$). The effective refractive index $n_{eff}$ is obtained by using an FEM-based mode solver in this paper. The previous pure plasmonic metal waveguide usually has a propagation distance of several micrometers (e.g., 3~5 $\mu$m [23]). For the present hybrid structure, the calculated propagation distance is shown in Fig. 3 (b) as the core width varies. From this figure, one sees that the propagation distance is on the order of $10^2$ $\mu$m (similar to that reported in Ref [17].), which is several tens of times of that for the nano-scale pure plasmonic metal waveguide [23].
The real part of $n_{\text{eff}}$ for different $h_{\text{SiO}_2}$ values as a function of core width $w_{\text{co}}$. The insets in Fig. 3(b) show the field distribution of the major component $E_y$ of the quasi-TM fundamental mode for $h_{\text{SiO}_2} = 50$ nm, 20 nm, and 5 nm. One sees that there is more optical field confined in the Si layer when the core width increases. This is why the effective index real($n_{\text{eff}}$) and the propagation distance $L_{\text{prop}}$ increases as the core width increases.

The insets in Fig. 3(b) show the field distribution of the major-component $E_y$ of the electrical fields. From these figures, one sees that there is more optical confinement in the Si layer when the core width increases. This is why the effective index real($n_{\text{eff}}$) and the propagation distance $L_{\text{prop}}$ increases as the core width increases, as shown in Fig. 3(a) and 3(b), respectively. We also see that the thickness $h_{\text{SiO}_2}$ of the SiO$_2$ nano-layer plays an important role for the propagation distance. When choosing a thinner SiO$_2$ layer, the propagation distance becomes smaller. For the case with a relatively large thickness $h_{\text{SiO}_2}$ (e.g., 50 nm), more power confined in silicon region. Therefore, when the core width decreases, the power confined in the silicon region will change greatly. This is why the influence of the core width on the propagation distances is significant when the thickness $h_{\text{SiO}_2}$ decreases.
is relatively large. For example, the propagation distance decreases from 432 μm to 76 μm when the core width decreases from 0.5 μm to 50 nm. In contrast, for the case with a very thin SiO₂ layer (e.g., 5 nm), the propagation distance is around 50 μm and does not change greatly as the core width decreases. In summary, the calculation results in Fig. 3 (b) show that the present hybrid plasmonic waveguide supports a propagation distance on the order of several tens of wavelength, which is useful to develop plasmonic waveguide devices.

One should note that there is a trade-off between the dimension of the plasmon waveguide and its propagation distance. Since it is easy to realize a propagation distance over 10⁴ μm by using a singlemode SOI nanowire when the core width \( w_{\text{co}} > 300 \) nm, in this paper, we focus on the potential of the present hybrid plasmonic waveguides for a relatively long propagation as well as a nano-scale (<100 nm) optical confinement (which is beyond the ability of conventional pure dielectric optical waveguides, e.g., SOI nanowires).

In the analysis above, the Si layer is etched through. We note that the aspect ratio of such a waveguide will be high when the core width becomes very small (e.g., ~100 nm). This will make the fabrication difficult in some degree. A solution to avoid this problem is using a shallowly-etched Si layer (i.e., \( h_{\text{Si,rib}} < H_{\text{Si}} \), as shown in Fig. 1). Figure 4 shows the propagation distance \( L_{\text{prop}} \) and the real part of the effective index as the Si rib height \( h_{\text{Si,rib}} \) decreases from 0.3 μm to 0. Here we consider the case with \( h_{\text{SiO₂}} = 5 \) nm (about \( \lambda/300 \)) and the core width \( w_{\text{co}} = 100 \) nm (about \( \lambda/15 \)) in this example. From this figure, one sees that the propagation distance increases as the rib height \( h_{\text{Si,rib}} \) decreases. According to the effective index method, a shallow silicon rib makes an equivalent layer with a larger index. This will make more power confined in silicon layer. Therefore, when the silicon rib decreases until zero, both the propagation distance and the real part of the effective index increase, as shown in Fig. 4.

![Fig. 4. For the cases of \( h_{\text{SiO₂}} = 5 \) nm and \( w_{\text{co}} = 100 \) nm, the real part of the effective refractive index \( n_{\text{eff}} \) and the propagation distance \( L_{\text{prop}} \) as the rib height \( h_{\text{Si,rib}} \) decreases. When the height \( h_{\text{Si,rib}} = 0 \), the Si part becomes a slab waveguide, in which case the propagation distance is close to 100μm (~60λ) and the fabrication is very easy because the etching becomes shallow. From Fig. 4, one sees that for this case (\( h_{\text{SiO₂}} = 5 \) nm, which is about \( \lambda/300 \)) the propagation distance increases monotonously as the rib height \( h_{\text{Si,rib}} \) decreases. Particularly, when \( h_{\text{Si,rib}} = 0 \), one obtains a hybrid plasmonic waveguide with a Si slab and the etching depth is much shallow. This makes the fabrication much simpler and easier. Meanwhile, the propagation distance is close to 100 μm, which is good for ultra-dense photonic integrations. In order to show the optical confinement for such a design with a Si slab, we calculate the field distribution of major-component \( E_y(x, y) \) for the quasi-TM polarization in the case with a ultra-small core width \( w_{\text{co}} = 50 \) nm (which is about \( \lambda/30 \)), as shown in Fig. 5. In the insets, we also show the field distributions \( E_y(x, 0) \) and \( E_y(0, y) \) for a clear view. From this figure, one sees the field is confined tightly in the low-index nano-layer. For the present case, the optical

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confinement is about $50 \text{nm} \times 5 \text{nm}$ ($\sim \lambda/300 \times \lambda/30$), which are related with the thickness of the low-index nano-layer and the core width.

Fig. 5. The field distribution of the quasi-TM fundamental mode with a nano-scale light confinement when $h_{\text{Si,rib}} = 0$, $h_{\text{SiO}_2} = 5 \text{nm}$, and $w_{\text{co}} = 50 \text{nm}$. The insets show the field distributions $E_y(x, 0)$ and $E_y(0, y)$. One sees that the optical field confinement at the vertical direction is on the order of $5 \text{nm}$ ($\sim \lambda/300$), which is related with the thickness of the low-index nano-layer. At the lateral direction, the optical field confinement is about $50 \text{nm}$ ($\sim \lambda/30$).

Figure 6 shows the calculated coupling length of two parallel hybrid plasmonic waveguides with the same parameters as those used for Fig. 5 ($h_{\text{Si,rib}} = 0$, $h_{\text{SiO}_2} = 5 \text{nm}$, and $w_{\text{co}} = 50 \text{nm}$ ($\sim \lambda/30$)). The coupling length is given by $L_c = \pi/(\beta_e - \beta_o)$, where $\beta_e$ and $\beta_o$ are the propagation constants of the even and odd super-modes of the system of the parallel waveguides (as shown by the inset). The coupling length is almost increases exponentially as the separation $D$ increases, which is similar to the conventional dielectric optical waveguides. When the separation is decreased to 100nm, the coupling length is as small as 2.8$\mu$m. This makes it
possible to realize a compact directional coupler (which is a basic element for photonic integration circuits).

3. Conclusion
We have studied a Si-based hybrid plasmonic waveguide with a metal cap for nano-scale light confinement. The present theoretical investigation has shown that a nano-scale (e.g., 50nm × 5nm) optical confinement is obtained with this hybrid plasmonic waveguide when it operates at 1550nm. At the same time, the low-loss enables the present hybrid plasmonic waveguide to have a relatively long propagation distance (on the order of 100 wavelengths). The fabrication the present hybrid plasmonic waveguide is simple and compatible with the standard processes for SOI wafers. Furthermore, our calculation has also shown that one could use a Si slab (instead of Si rib) under the metal cap (see Fig. 5), in which way the fabrication becomes much simpler and easier. With the present hybrid plasmonic waveguide, it is also possible to realize a low-voltage compact optical modulator when the nano-layer material between the Si layer and the metal layer has a high electro-optical coefficient. In order to connect with pure SOI nanowire when necessary, it is possible to introduce mode transformers in the similar way shown in Ref [24], by consisting of several adiabatic tapers.

Acknowledgement
This project was partially supported Zhejiang Provincial Natural Science Foundation (No. J20081048).
Low-loss hybrid plasmonic waveguide with double low-index nano-slots

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Abstract: A hybrid plasmonic waveguide with double low-index nano-slots is introduced. The fabrication is simple and compatible with the standard processes for SOI wafers. The theoretical investigation shows that the present hybrid plasmonic waveguide has a low loss and consequently a relatively long propagation distance (at the order of several tens of λ). For TE polarization, there is a strong field enhancement in the double nano-slots. More power is confined in the low-index nano-slots for a smaller core width. For a 50nm-wide hybrid plasmonic waveguide with double 10nm-wide slots, the power confinement factor in the nano-slots is as high as 85% and the effective area is as small as 0.007m² at 1550nm. Consequently, the power density in the nano-slots becomes very high, e.g., >120m⁻², which is very desired for many applications. For the present hybrid plasmonic waveguide, the lateral dimension could be less than 50nm and the calculated decoupled separation for two parallel identical waveguides is only 0.62λ, which is helpful to realize photonic integration circuits with ultra-high integration density.

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OCIS codes: (240.6680) Surface plasmons; (250.5300) Photonic integrated circuits; (130.2790) Guided waves

References and links
1. Introduction

In order to realize nanophotonic integrated circuits (PICs) with high-integration density, we need to develop nano-scale optical waveguides. It is well known that Si-on-insulator (SOI) nanowires with an ultra-high index-contrast \( n_i/g_1\) and photonic crystal waveguides [3] could provide sub-wavelength optical confinement. However, these pure dielectric nanophotonic waveguides are still subject to the optical diffraction limit, which prevents the reduction of the waveguide dimension to the order of 100nm. In contrast, surface plasmon (SP) waveguides [4–12] pave a way to obtain optical confinement in the scale of 100nm or less, which makes it attractive as a potential candidate for a true nano-scale waveguiding and confinement of light. Furthermore, surface plasmon (SP) waveguide has the ability of sending both electric and photonic signals along the same circuit, which creates a bridge to connect optics and electronics naturally.

In the past years several three-dimensional structures have been reported to support highly localized fields, e.g. narrow gaps between two metal interfaces [5–8,11–13] and V-grooves in metals [9,10]. Unfortunately, such nano-scale optical waveguides are usually pretty lossy and consequently the propagation distance is usually at the scale of several micrometers.

Recently, hybrid plasmonic waveguides have attracted lots of attention due to the relatively long propagation distance, e.g., the structure with a dielectric cylinder above a metal surface [14], metal-GaAs-gap structure [15], a lossy dielectric nanowire adjacent to a metallic surface [16,17], and a Si nanowire with a metal cap [18,19]. The concept of the hybrid plasmonic waveguide was also used to lower the propagation loss of metal stripe optical waveguides [20]. In our previous work [19], our proposed Si-based hybrid plasmonic waveguide with a metal cap provides a nano-scale optical confinement as well as a long propagation distance when it operates at quasi-TM polarization. Recently the coupling between this type Si-based hybrid plasmonic waveguide and a SOI nanowire was investigated [21]. Some experimental results have also been demonstrated in Ref [22], for this type Si-based hybrid plasmonic waveguide.

In this paper, we introduce a novel low-loss hybrid plasmonic waveguide with low-index double nano-slots. The present hybrid plasmonic waveguide works for TE polarization. By introducing double low-index nano-slots, the present hybrid plasmonic waveguide provides a very high power density in the region of low-index slots due to the field-enhancement resulting from the effects of electric-field discontinuity and surface plasmonics. Due to the field enhancement in the low-index nano-slots, a small effective area is achieved. The high power density in the low-index nano-slots is also helpful for some applications, e.g., nonlinear optics, optical sensing, etc. The present hybrid plasmonic waveguide has very small decoupled separation for two parallel identical waveguides, which is helpful to realize high density of photonic integrations. The theoretical investigation also shows that a relatively long
propagation distance can be achieved. More importantly, the fabrication for the present hybrid plasmonic waveguide is simple and CMOS-compatible.

2. Waveguide structure and analysis

Figure 1 shows the cross section of the present structure, which consists of a silicon-on-insulator (SOI) rib and metal cladding. There is a thin SiO$_2$ layer between the Si region and the metal cladding. In this way, double nano-slots are formed at both sides of the Si rib. The SiO$_2$ layer at the top of the Si rib is relatively thick to minimize the metal absorption. For such a structure, the fabrication is simple and CMOS-compatible.

![Diagram of waveguide structure](image)

Fig. 1. The cross section of the present hybrid plasmonic waveguide with double low-index slots.

Figure 2 (a)-(d) show the proposed fabrication process flow for the present nano-scale hybrid plasmonic waveguide. As shown in Fig. 2 (a), one could use a standard SOI wafer. An alternative way is to use the PECVD (plasma enhanced chemical vapor deposition) technology to deposit the SiO$_2$ and alpha-Si thin films on a Si substrate. The next step is to form a SiO$_2$ thin film with a thickness of 100~200nm by using the PECVD technology or the process of thermal oxidation, as shown in Fig. 2 (a). The photoresist thin film is then formed on the SiO$_2$ layer and the waveguide patterns are defined by using an E-beam lithography to have a high resolution. A dry etching process is then used to etch through the layers of SiO$_2$ and Si (see Fig. 2 (b)). Then a very thin SiO$_2$ layer (5-50nm) is formed at the sidewall of the Si rib by using thermal oxidation (see Fig. 2 (c)). The thickness of the SiO$_2$ layer at the sidewall can be controlled very well by controlling the thermal-oxidation time. Due to the thermal oxidation, the Si rib will become narrower slightly (reduced by about 2$w_{SiO2}$/2.7). Finally a metal film is deposited on the top, as shown in Fig. 2 (d). With the present waveguide structure, there is no need for metal patterning/etching, which makes the fabrication much easier.

When the SiO$_2$ layer at both sides of the Si rib is thick (e.g., 0.5μm-thick) and the Si rib is relatively wide (e.g., 400nm), the fundamental mode field is confined well in the Si region and consequently the metal layer will hardly influence the mode field distribution. In this case, the present structure behaves like a regular SOI nanowire. However, the metal layer will give a significant influence to the guided mode when the SiO$_2$ thickness becomes small (e.g., <50 nm). As an example, we choose the following geometrical dimensions: the Si rib width $w_{co} = 50$nm, the metal thickness $h_m = 200$nm, the SiO$_2$ slot width $w_{SiO2} = 20$ nm, the Si rib height $h_{Si} = 340$nm, and the SiO$_2$ upper-cladding thickness $h_{SiO2} = 300$nm. We choose the wavelength $\lambda = 1550$nm and the corresponding refractive indices for all the involved materials as $n_{metal} = 0.1453 + 11.3587i$ (Ag) [14], $n_{SiO2} = 1.445$, and $n_{Si} = 3.455$. By using a full-vectorial finite-element-method mode solver (COMSOL), we calculate the field distribution of the major-component $E_x(x, y)$ for the quasi-TE fundamental mode, as shown in Fig. 3. In our calculation, the computational window is large enough ($-1\mu m\leq x \leq 1\mu m$, $-1\mu m\leq y \leq 1\mu m$), and the perfect-
electric-conductor boundary-condition is used. In order to see the profile more clearly, we also plot the field distributions \( E_{x}(x, y_0) \) and \( E_{x}(x_0, y) \) (the coordinate system is shown in Fig. 1). Here \( x_0 = w_{Si}/2 + w_{SiO2}/2 \) and \( y_0 = h_{Si}/2 \). It can be seen that the present hybrid plasmonic waveguide provides a very good confinement for the optical field even when the waveguide core is as small as 50nm (or even smaller).

Fig. 2. The proposed fabrication processes: (a) Form a ~100nm-thick SiO\(_{2}\) film; (b) E-beam lithography and ICP etching; (c) Thermal oxidation: 10–50nm-thick SiO\(_{2}\); (d) Metal deposit: 100–200nm-thick.

From the curve of \( E_{x}(x, y_0) \) in Fig. 3, one sees that the field at the two 10nm-SiO\(_{2}\) nano-slots is enhanced greatly, i.e., the electric field in the SiO\(_{2}\) region is much higher than that in the Si region. For a pure-dielectric nano-slot waveguide, there is a similar field enhancement in the low-index region because of the strong discontinuity of the normal component of the electric field at the high-index-contrast interface [2,19]. For the hybrid plasmonic waveguide, the principle is different partially [19]. At the Si-SiO\(_{2}\) side interface, there is a strong discontinuity of the normal component of the electric field, which is the same as that in a pure-dielectric vertical slot waveguide. On the other hand, at the SiO\(_{2}\)-metal interface, surface plasmon (SP) wave is excited. The electric field of the excited SP wave decays exponentially at both sides of the interface and has a peak at the interface. In the thin SiO\(_{2}\) nano-slots, the field distribution could be regarded as the sum of two exponential functions. When the SiO\(_{2}\) layer is very thin (smaller than the evanescent penetration depth), the field at SiO\(_{2}\) layer is enhanced greatly, as shown in Fig. 3. In the present hybrid plasmonic waveguide, the double nano-slots help to achieve a very high power confinement factor at the low-index regions even when the slot area is very small (discussed below).
First we consider the case with a relatively thick SiO$_2$ upper-cladding, e.g., $h_{	ext{SiO}_2} = 300$nm, which is helpful to reduce the metal absorption at the top. Figure 4 (a) shows the real part of the effective refractive index of the present hybrid plasmonic waveguide as the core width $w_{	ext{co}}$ varies. Here the thickness of SiO$_2$ nano-slot is chosen as $w_{	ext{SiO}_2} = 50, 30, 20,$ and $10$nm. For a given waveguide width $w_{	ext{co}}$, one has a larger effective index $n_{	ext{eff}}$ for the case with a thinner SiO$_2$ layer. When the core width $w_{	ext{co}}$ decreases, the effective index decreases. This can be explained by the power confinement factors in SiO$_2$ nano-slots and Si region. Figures 4 (b) and 4(c) shows the percentages of the powers confined in the SiO$_2$ nano-slots and Si region, respectively. From these figures, one sees that as the core width $w_{	ext{co}}$ decreases the power confinement factor $P_{	ext{SiO}_2}$ in the SiO$_2$ nano-slots increases while the power confinement factor $P_{	ext{Si}}$ confined in the Si region decreases. When the core width decreases to sub-100nm, the power confinement factor $P_{	ext{SiO}_2}$ can be as high as 85%. Consequently, one could have a very high power density in the SiO$_2$ nano-slots, as shown in Fig. 4(d). Here the power density is normalized with the total waveguide optical power [2]. For the case of $w_{	ext{SiO}_2} = 10$nm, the normalized power density is higher than 120$\mu$W$^{-2}$. Even when the core width decreases to 30nm (see the curve for $w_{	ext{SiO}_2} = 10$nm in Fig. 4(b)), there is still a guided mode supported in the hybrid optical waveguide, which is very interesting to have nano-scale light confinement (similar to the other nano-scale metal waveguides). Due to the enhanced field distribution, the present hybrid plasmonic waveguide could have an ultrasmall effective area, as shown in Fig. 4(e). The effective area $A_{\text{eff}}$ is defined as [14]
where $P(x, y)$ is the energy flux density (Poynting vector) of the quasi-TE fundamental mode, and $P(x, y) = E(x, y) \times H(x, y)$.

\[ A_{\text{eff}} = \frac{\int P(x, y) \, dx \, dy}{\max|P(x, y)|}, \]  

(1)

Fig. 4. For the cases of $w_{\text{slot}} = 10\,\text{nm}, 20\,\text{nm}, 30\,\text{nm}, \text{and} 50\,\text{nm}$, (a) the real part of the effective index of the quasi-TE fundamental mode; (b) the power confinement factor in the low-index slots $P_{\text{SiO}_2}$; (c) the power confinement factor in the Si rib $P_{\text{Si}}$; (d) the normalized power density; (e) the effective areas $A_{\text{eff}}$; (f) the propagation distance $L_{\text{prop}}$. Here we choose a relatively thick SiO$_2$ up-cladding $h_{\text{SiO}_2} = 300\,\text{nm}$ and $h_{\text{Si}} = 340\,\text{nm}$.

From Fig. 4(e), one sees that a smaller effective area $A_{\text{eff}}$ is obtained when choosing a thinner SiO$_2$ slot. For example, the effective area $A_{\text{eff}}$ is only about 0.007$\mu$m$^2$ for a 50nm-wide
waveguide with double 10-nm slots. It is possible to reduce the effective area further if reducing the thickness of SiO$_2$ nano-slots. This is very useful for nonlinear optical applications or optical modulations.

On the other hand, for the realization of plasmonic waveguide devices, it is very important to allow a long propagation distance, $L_{\text{prop}}$, which is defined as the distance that the amplitude of the field attenuates to $1/e$, i.e., $L_{\text{prop}} = 1/(n_{im}k_0)$, where $n_{im}$ is imaginary part of the effective refractive index $n_{eff}$ and $k_0$ is the wave number in vacuum ($k_0 = 2\pi/\lambda$). The effective refractive index $n_{eff}$ is obtained by using an FEM-based mode solver in this paper. A pure plasmonic metal waveguide usually has a propagation distance of several micrometers (e.g., 3-5 μm). For the present hybrid structure, the calculated propagation distance is shown in Fig. 4(f) as the core width $w_{co}$ varies. From this figure, one sees that the propagation distance usually ranges from several tens of microns to 200 microns, which is similar to those reported hybrid plasmonic waveguides [14].

From these figures, one sees that the thickness $h_{SiO2}$ of the SiO$_2$ nano-slot plays an important role for the propagation distance. For the case with a thinner SiO$_2$ layer, the propagation distance becomes smaller. This is because the field amplitude at the interface between the SiO$_2$ nano-slot and the metal layer becomes higher when the SiO$_2$ nano-slot is thinner. We should note that there is a trade-off between the dimension of the plasmon waveguide and its propagation distance. Since it is easy to realize a propagation distance over $10^3$ μm by using a singlemode SOI nanowire when the core width $w_{co} > 300$ nm, we focus on the potential of the present hybrid plasmonic waveguides for a relatively long propagation as well as a nano-scale (~100nm) optical confinement (which is beyond the ability of conventional pure dielectric optical waveguides, e.g., SOI nanowires).

In the above analysis, a relatively thick SiO$_2$ upper-cladding is considered to prevent the absorption from the metal at the top. A thick SiO$_2$ upper-cladding will introduce a high aspect ratio especially for a very narrow waveguide, which makes the etching not easy. Thus, a thinner SiO$_2$ upper-cladding is preferred for easy fabrication. Figure 5(a) shows the propagation distance $L_{\text{prop}}$ as the core width $w_{co}$ varies for the cases of $h_{SiO2} = 20$, 50, 100, 150, 200, 250, and 300nm; (b) the propagation distance $L_{\text{prop}}$ as the thickness $h_{SiO2}$ varies for the cases of $w_{co} = 100$, 150, and 200nm. Here the slot width is fixed to $w_{slot} = 20$nm and the Si rib height $h_{Si} = 340$nm.

Fig. 5. (a) The propagation distance $L_{\text{prop}}$ as the core width $w_{co}$ varies for the cases of $h_{SiO2} = 20$, 50, 100, 150, 200, 250, and 300nm; (b) the propagation distance $L_{\text{prop}}$ as the thickness $h_{SiO2}$ varies for the cases of $w_{co} = 100$, 150, and 200nm. Here the slot width is fixed to $w_{slot} = 20$nm and the Si rib height $h_{Si} = 340$nm.

In the above analysis, a relatively thick SiO$_2$ upper-cladding is considered to prevent the absorption from the metal at the top. A thick SiO$_2$ upper-cladding will introduce a high aspect ratio especially for a very narrow waveguide, which makes the etching not easy. Thus, a thinner SiO$_2$ upper-cladding is preferred for easy fabrication. Figure 5(a) shows the propagation distance for the present hybrid plasmonic waveguide with different thicknesses $h_{SiO2}$ for the SiO$_2$ upper-cladding. Here the slot width is fixed to $w_{slot} = 20$nm and the Si rib height $h_{Si} = 340$nm. It can be seen that the propagation distance for a wider waveguide (e.g., $w_{co} = 400$nm) decreases greatly as the thickness $h_{SiO2}$ decreases. On the other hand, the propagation distance does not change much for a narrow waveguide (e.g., $w_{co} = 100$nm), which is more interesting for nano-photonic integration. In Fig. 5(b), the propagation distances for the waveguides with $w_{co} = 200$, 150, 100nm are shown as the thicknesses $h_{SiO2}$ decreases. One sees that the propagation distance decreases around 10% when the thicknesses...
$h_{SiO2}$ decreases from 300nm to 20nm. In the following part, we choose $h_{SiO2} = 150$ nm to make a trade-off.

When considering the integration density, it is important to examine how closely two adjacent parallel waveguides can be placed on a chip so that the cross talk (XT) between them due to coupling is negligible (e.g., $XT < XT_0 = -25$ dB) after a propagation distance $l_0$ [23]. The crosstalk due to the evanescent coupling between two parallel waveguides is given by [23]

$$XT = 20\log\left[\sin\left(0.5\pi z / L_c\right)\right],$$

where $L_c$ is the coupling length and $z$ is the length of the coupling section. For two identical parallel optical waveguides, the coupling length can be easily estimated with formula

$$L_c = \pi / (\beta_o - \beta_e),$$

where $\beta_o$ and $\beta_e$ are the propagation constants of the odd and even supermodes of the two parallel waveguides, respectively, and can be calculated by using a full-vectorial FEM mode-solver.

According to the requirement of $XT < XT_0$ after a propagation distance, the coupling length $L_c$ should be large enough, i.e.,
For example, one obtains $L_{c(\text{min})} = 27.9 l_0$ when $X_{T_0} = -25 \text{dB}$. According to the propagation distance, usually length $l_0$ of the parallel part of two plasmonic waveguides in a chip is no more than 50μm and thus it is enough to neglect the coupling when the coupling length is larger than 1395μm (for $X_{T_0} = -25 \text{dB}$), i.e., $L_{c(\text{min})} = 1395 \mu m$. The separation $s_{dc}$ which gives a coupling length $L_{c(\text{min})} = 1395 \mu m$ is defined as the decoupling separation.

Figure 6(a) shows the calculated coupling length $L_c$ of two parallel hybrid plasmonic waveguides as the core width varies from 300nm to 50nm for some given separations $s = 800, 700, ..., 100 \text{nm}$. The other parameters are given as follows: $h_{Si} = 340 \text{nm}$, $w_{SiO_2} = 10 \text{nm}$, and $h_{SiO_2} = 150 \text{nm}$. The coupling length is given by $L_c = \pi / (\beta_0 - \beta_c)$. From Fig. 6(a) one sees that there is an optimal core width for maximal coupling length when the separation is large (this is similar to the case of pure-dielectric evanescent coupling [23]). Figure 6(b) shows the coupling length as the separation increases for a fixed core width $w_{co} = 50 \text{nm}$. It can be seen that the coupling length increases almost exponentially as the separation $D$ increases. This is also similar to the case of a conventional dielectric optical waveguide. According to the above definition, the decoupling separation $s_{dc}$ is as small as 620nm, which is helpful to have very dense photonic integration. On the other hand, the coupling length is only several micron when a small separation is chosen (e.g., $s = 100 \text{nm}$). This is good for an ultracompact directional coupler (which is a basic element for nanophotonic integration circuits).

3. Conclusion

We have studied a Si-based hybrid plasmonic waveguide with double low-index nano-slots for nano-scale light confinement as well as relatively long propagation distance (several tens of microns). Due to the field enhancement in the low-index nano-slots for TE polarization, an ultrasmall effective area is achieved (e.g., 0.007μm$^2$ or less at 1550nm). When the core width decreases, there is more power confined in the low-index nano-slots. The power confinement factor could be as high as 85%. In this case, the power density in the nano-slots becomes very high, e.g., $>120 \mu m^{-2}$, which is very desired for some application like optical manipulation, optical nonlinearity, etc. It has also shown that the lateral dimension of the present hybrid plasmonic waveguide could be as small as 50nm. And the coupling between two adjacent waveguide is very small even though they are placed very closely. It has shown that the decoupled separation for two parallel identical waveguides is only 0.62μm. This is very helpful to realize photonic integration circuits with ultra-high integration density. Furthermore, as the proposed fabrication flow, the fabrication of the present hybrid plasmonic waveguide is simple and compatible with the standard processes for SOI wafers.

Acknowledgment

This project was partially supported by Zhejiang Provincial Natural Science Foundation (No. R1080193) and the National Nature Science Foundation of China (No. 60688401).
Ultra-low-loss high-aspect-ratio Si$_3$N$_4$ waveguides

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Abstract: We characterize an approach to make ultra-low-loss waveguides using stable and reproducible stoichiometric Si$_3$N$_4$ deposited with low-pressure chemical vapor deposition. Using a high-aspect-ratio core geometry, record low losses of 8-9 dB/m for a 0.5 mm bend radius down to 3 dB/m for a 2 mm bend radius are measured with ring resonator and optical frequency domain reflectometry techniques. From a waveguide loss model that agrees well with experimental results, we project that 0.1 dB/m total propagation loss is achievable at a 7 mm bend radius with this approach.

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OCIS codes: (130.0130) Integrated optics; (230.7390) Waveguides, planar.

References and links


1. Introduction

Compared to bulk and fiber optic systems, photonic integrated circuits (PICs) can offer improved performance and stability in a smaller footprint and at a lower cost. Many targeted PIC applications, for example, communication network filters and multiplexers [1], optical gyroscopes rotational velocity sensors [2], optical buffers [3], and true-time-delay antenna beam-steering networks [4], require large on-chip optical path lengths and/or high-quality-factor resonators. As performance demands on these applications increase, waveguides with ultra-low propagation loss become necessary.

With propagation losses less than 1 dB/cm at $\lambda = 1550$ nm for bend radii down to 0.5 mm, silica-on-silicon planar lightwave circuits (PLCs) have been most successful in meeting this challenge. In a PLC, ultra-low loss is commonly achieved with a low-index-contrast core buried between 10 to 20 microns of silicon dioxide [5]. The core is typically square or nearly-square with side lengths of several microns in order to maintain low polarization sensitivity, efficient fiber coupling, and single-mode operation for passive communication network applications. Several core materials and deposition processes with varying index contrasts have been pursued within this general framework. Propagation loss as low as 5 dB/m at a 2 mm bend radius has been reported for silicon oxynitride cores having an index contrast of 2.5% [6]. Phosphorus-doped SiO$_2$ cores with an index contrast of 0.6-0.7% have reached losses of 0.85, 1.22, and 4.72 dB/m at 30, 20, and 10 mm bend radii, respectively [7]. In [8], germanium-doped SiO$_2$ waveguides deposited with flame hydrolysis at an index contrast of...
0.75% show an average propagation loss of 0.3 dB/m. In this case, however, the large core dimensions result in a “quasi-single-mode” waveguide, meaning that higher-order modes can be excited but are lost while propagating through waveguide bends.

Stoichiometric silicon nitride has a higher refractive index contrast with SiO₂ than the above core materials and offers the benefits of increased material stability and high refractive index regularity. Moreover, Si₃N₄ films deposited with low-pressure chemical vapor deposition (LPCVD) have thicknesses controllable to the nanometer scale and exhibit low (< 0.4 nm) surface roughness, a quality necessary for maintaining low scattering loss at the top and bottom core-cladding interfaces [9]. Since interfacial scattering loss scales quadratically with the difference between the core and cladding permittivities [10], the high refractive index contrast (around 25%) of stoichiometric Si₃N₄ with SiO₂ could potentially prevent the realization of ultra-low-loss waveguides made from this material. Sidewall scattering, the primary contributor to loss in high-index-contrast planar waveguides, can be minimized, however, by using a high-aspect-ratio core geometry in which the width of the waveguide far exceeds the thickness. This allows one to keep the benefits of a stoichiometric material while also attaining low propagation loss.

In this paper, we report on single-mode ultra-low-loss waveguides (ULLWs) fabricated with TriPlex™ LPCVD Si₃N₄ technology [11] for a design wavelength of 1550 nm. As the core refractive index is fixed, a design-by-geometry approach allows ultra-low loss to be achieved across a range of millimeter-scale bend radii using the high-aspect-ratio (width:thickness > 10:1) and low-confinement core design shown to scale in Fig. 1. As reported in [12], the confinement of the fundamental TM mode, $\Gamma_{\text{TM}}$, is much lower than that of the fundamental TE mode, $\Gamma_{\text{TE}}$, in such high-aspect-ratio designs, and the high birefringence increases the polarization maintaining properties of the waveguide. For the 80 nm-thick waveguide shown in Fig. 1, $\Gamma_{\text{TE}}/\Gamma_{\text{TM}} \approx 7.6$, so that only the propagation loss and design for the fundamental TE mode are considered. We begin with an outline of the waveguide loss model used in the design of the waveguides (Section 2). We then discuss the characterization of ultra-low waveguide loss using ring resonator and optical frequency domain reflectometry (OFDR) measurements (Section 3). Finally, we use the characterization results along with our model to project how stoichiometric Si₃N₄ waveguides with propagation loss on the order of 0.1 dB/m can be realized (Section 4).

Fig. 1. (a) Cross-section (to scale) of the Si₃N₄-core waveguides designed and characterized in this paper along with simulated (λ = 1550 nm) fundamental (b) TE and (c) TM modes (same scale) of an 80 nm core waveguide. The spacing between contours is 6 dB down to the minimum contour of ~30 dB.
2. Loss model

In a planar waveguide, the total propagation loss of a mode is the sum of many contributions including material absorption, Rayleigh scattering, interfacial scattering, substrate leakage, bend radiation, and crosstalk loss. At the cost of increased fabrication time, substrate leakage can be rendered negligible (~0.001 dB/m for the layers shown in Fig. 1(a)) through the deposition of thick cladding layers. Similarly, crosstalk loss can also be neglected if sufficient space is included between waveguide cores. Material absorption loss in a PLC is primarily due to absorptive bond resonances, typically involving hydrogen, present within the core and cladding layers. In [13], a high temperature (1000 °C) anneal is shown to decrease the concentration of loss-dominating N-H bonds in SiON material to a level well below the detection limit of common measurement techniques or less than 0.5x10^{21} cm^{-3}. An extrapolation from the available data taken at λ = 1530 nm in [13] suggests that N-H bond concentrations on the order of 1x10^{20}, 1x10^{19}, and 1x10^{18} cm^{-3} would contribute ~1, 0.1, and 0.01 dB/m to the total propagation loss in a low-confinement Si3N4 waveguide with Γ_x > 0.1. Since the waveguides considered in this paper are low-confinement and annealed for several hours above 1100 °C, material loss is not included in the model. Rayleigh scattering, accounting for a propagation loss on the order of 0.1 dB/km, is also negligible compared to interfacial scattering and bend radiation loss in planar dielectric waveguides [14]. Since an additional loss contribution can arise from scattering and bend-induced conversion to higher order modes in a multimode waveguide, core geometries should support a single guided mode at λ = 1550 nm. Thus, a model that considers scattering loss at all core-cladding interfaces, bend radiation loss, and single-mode core geometries is employed.

2.1 Interface scattering loss model

In order to include the full effect of the core geometry, we use a three-dimensional volume current method to calculate interfacial scattering loss [15,16]. In this approach, the interface roughness profile, f(z) in Fig. 2(a), gives the deviation of the core-cladding interface from its mean location, which is taken to be zero. The deviation is assumed to be a function of the propagation direction alone, yielding a columnar description of the interface roughness. The radiation loss due to scattering from the refractive index inhomogeneity at this rough interface is then modeled as an equivalent polarization volume current density. This equivalent source is proportional to the electric field at the core-cladding interface of the waveguide. As the mean deviation in the interface location is typically a small fraction of the waveguide cross-section, the mode of the unperturbed waveguide can be used as an accurate approximation of the field distribution in the rough waveguide. For example, at the sidewall interface shown in Fig. 2 and for the waveguide’s fundamental TE mode [15]:

\[
\hat{J}(\mathbf{r}) = -j\omega\varepsilon_0(n_{core}^2 - n_{clad}^2)\hat{E}_{TE}(x, y)\delta(y)\delta(z),
\]  

(1)

where \(-\frac{\lambda}{2} \leq \mathbf{r} \leq \frac{\lambda}{2}\), ω is the radial frequency of the light propagating in the waveguide, \(\varepsilon_0\) is the permittivity of free space, \((n_{core}^2 - n_{clad}^2)\) is the difference of the core and cladding relative dielectric constants, \(\hat{E}_{TE}(x, y)\) is the electric field of the fundamental TE mode of the waveguide, and \(\delta(y)\) is the Dirac delta function. The x, y, and z components of the electric field at each core-cladding interface are calculated numerically with a fully vectorial finite-difference algorithm incorporated into MATLAB [17].
As shown in Fig. 2(b), we assume that the autocorrelation function of the roughness profile, \( R(u) = \langle f(z) f(z + u) \rangle \), measured at the core-cladding interface of a waveguide fits well to an exponential model [10,15,16]:

\[
R(u) \approx \sigma^2 \exp \left( -\frac{|u|}{L_c} \right),
\]

where \( \sigma^2 \), the mean square deviation, and \( L_c \), the correlation length of the roughness, are the model fitting parameters. Furthermore, the power spectrum of the roughness, \( \tilde{R}(\Omega) \), is related to the autocorrelation function by a Fourier transform [15]:

\[
\tilde{R}(\Omega) = \mathcal{F}\{ R(u) \} \approx \frac{2\sigma^2 L_c}{1 + L_c \Omega^2}.
\]

The power spectrum is the intensity with which a spatial frequency \( \Omega \) is present in the interface roughness profile. As such, the product of the power spectrum with the power radiation pattern of the current source in Eq. (1) forms the final power radiation pattern of the interface scattering’s equivalent current source, and the total power per unit length radiated by this source is calculated as:

\[
\frac{P_{\text{rad}}}{L} = \int_0^\pi \int_0^{2\pi} \left( \mathbf{S} \cdot \hat{r} \right) \tilde{R} \left( \beta - k_0 n_{\text{clad}} \hat{r} \cdot \hat{z} \right) r^2 \sin \theta d\theta d\phi,
\]

where \( \left( \mathbf{S} \cdot \hat{r} \right) \) is the outward directed Poynting vector due to the current source in Eq. (1), \( \beta \) is the propagation constant of the mode, and \( k_0 \) is the free space wavenumber. The integration of \( \tilde{R}(\Omega) \) is limited to spatial frequencies between \( \left( \beta - k_0 n_{\text{clad}} \hat{r} \cdot \hat{z} \right) \) and \( \left( \beta + k_0 n_{\text{clad}} \hat{r} \cdot \hat{z} \right) \), as this interval is responsible for the roughness-induced coupling to radiation modes [10]. In order to calculate the power loss coefficient \( \alpha \) due to the radiation from the interface, \( P_{\text{rad}}/L \) is divided by the total \( z \)-directed Poynting vector in the waveguide mode. If the roughness profiles at each core-cladding interface are uncorrelated, Eq. (4) can be applied independently at each rough surface in order to calculate the total scattering loss.

For low index contrast waveguides, the power radiated from the equivalent current source is calculated to good approximation by assuming that the current source radiates into a uniform medium with refractive index equal to that of the cladding. Under this assumption, \( \left( \mathbf{S} \cdot \hat{r} \right) \) can be calculated using the magnetic vector potential in the Lorenz gauge [15,16]. Since Si\textsubscript{3}N\textsubscript{4} has a relatively high index contrast of ~25% with SiO\textsubscript{2}, the waveguide core’s effect on the power radiation profile of the equivalent current source must be considered. This is accomplished analytically using the dyadic Green’s functions of one-layer media presented in [15]. The final expression for \( \left( \mathbf{S} \cdot \hat{r} \right) \), valid for any index contrast is then:
\[
\langle \hat{S} \cdot \hat{r} \rangle = \frac{\pi \sigma n_{\text{clad}}}{2 \lambda_0 \eta_0} \left( n_{\text{core}}^2 - n_{\text{clad}}^2 \right)^2 \operatorname{Re} \left( \frac{G}{G'} \right) \| F_{\text{shape}}(\theta, \phi) \|^2 \| S_{\text{pol}}(\theta, \phi) \|^2, \tag{5}
\]

where \( \eta_0 \) is the impedance of free space, \( \lambda_0 \) is the free space wavelength, \( \frac{G}{G'} \) is the dyadic Green’s function for one-layer media, \( \| F_{\text{shape}}(\theta, \phi) \|^2 \) is the power array factor corresponding to the electric field shape at the sidewall as defined in [15], and \( \| S_{\text{pol}}(\theta, \phi) \|^2 \) is the normalized power radiation profile of a point source with \( x, y, \) or \( z \) polarization, e.g. \( S_{\text{pol}}(\theta, \phi) = \sin^2(\theta) \) for \( x \) polarization. Since we have extended the scattering loss model in [15] to include scattering from the top and bottom core-cladding interfaces, an additional field shape, \( \psi_{\text{BB}}(\psi, \phi, z) \), is used to better match the \( z \) component of \( E \) there:

\[
\psi_{\text{BB}}(\psi, \phi, z) = \frac{8b \left[ 1 + \frac{\pi - bn_{\text{sid}} k_0 \cos(\phi) \sin(\theta) + bn_{\text{sid}} k_0 \cos(\phi) \sin(\theta)}{(\pi - bn_{\text{sid}} k_0 \cos(\phi) \sin(\theta)) + bn_{\text{sid}} k_0 \cos(\phi) \sin(\theta)} \right]}{\pi - bn_{\text{sid}} k_0 \cos(\phi) \sin(\theta)}, \tag{7}
\]

where \( b \) is the waveguide core width as shown in Fig. 2. In [18], the TE propagation loss in a 200 \( \times \) 500 nm silicon nanowire \((n_{\text{core}} - n_{\text{clad}} = 2.0)\) is measured to be \( \sim 33 \) dB/cm at \( \lambda_0 = 1540 \) nm. Using the measured \( \sigma \) and \( L_c = 50 \) nm, the model predicts a scattering loss of 33.41 dB/cm, giving a \( \sim 1\% \) error.

### 2.2 Bend radiation loss model

To simulate bend radiation loss, the curved waveguide is transformed into an equivalent straight waveguide through a conformal mapping of the refractive index [19]. A “staircase” consisting of 200 uniform layers approximates the resultant non-uniform refractive index profile, and an eigenmode expansion method (CAMFR [20]) is used to solve for the modes of this structure. With a non-uniform refractive index profile, the mode solution becomes radiative wherever the refractive index is greater than the modal index. By adding perfectly matched layers (PML) at the boundaries of the simulation window, this radiation loss is quantified in the imaginary part of the modal index [20]. From such a model, it is intuitive that higher confinement structures with larger modal indices result in lower bend loss for a given bend radius.

### 2.3 Waveguide design from loss model

We now consider the design of Si₃N₄-core strip waveguides as shown in Fig. 1. Scattering loss due to the sidewall, top, and bottom interfaces is plotted for different core geometries in Fig. 3. The roughness parameters at opposite sidewalls and at the top and bottom interfaces are assumed to be equal, and only results from core geometries operating in the single-mode regime are shown. Typical sidewall roughness correlation lengths resulting from planar waveguide fabrication processes range from 20 to 70 nm [21], and scattering loss at \( \lambda_0 = 1550 \) nm depends linearly on \( L_c \) in this regime. To be consistent with previous scattering loss analyses [15,16], a value of \( L_c = 50 \) nm is assumed for all plots with simulated sidewall scattering loss. From our own atomic force microscope (AFM) measurements of Si₃N₄ films (Fig. 2(b)), typical top surface roughness correlation lengths are closer to 30 nm, and this value is assumed for all plots with simulated top and bottom surface scattering loss. As Eq. (3) contains the only dependence of scattering loss on mean square deviation, loss can be calculated from Fig. 3 in units of dB/m through multiplication by the \( \sigma^2 \) that is characteristic of that interface:

#136596 - $15.00 USD     Received 13 Oct 2010; revised 9 Dec 2010; accepted 13 Dec 2010; published 3 Feb 2011
(C) 2011 OSA 14 February 2011 / Vol. 19, No. 4 / OPTICS EXPRESS  3168

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The interfacial scattering loss curves in Fig. 3 are most easily understood within the context of Eq. (1) and the relationship between mode size, mode confinement, and core geometry presented in Fig. 4. In Fig. 3(a) and Fig. 4(a), it can be seen that sidewall scattering loss increases with increasing core width at first as the mode transitions from being “squeezed out” to being more confined in the lateral direction. Sidewall scattering loss then reaches its peak magnitude where the lateral mode diameter is small, and the integral of \( \hat{E}_{\text{TE}}(x,y) \) along the sidewall has its greatest magnitude. After the peak in sidewall scattering loss and the minimum in mode diameter have been reached, Fig. 4 shows that the mode is highly confined to the waveguide core along the lateral dimension. A further increase of the core width then decreases the optical intensity (W/m²) in the core, yielding a corresponding decrease in scattering loss according to Eq. (1). Contrary to the sidewall case, loss from the top and bottom surfaces increases monotonically with core thickness (Fig. 3(b)), as the Si\(_3\)N\(_4\) core thicknesses considered are not large enough to achieve high mode confinement along the vertical dimension (Fig. 4(b)). Scattering from the top and bottom interfaces also increases monotonically with core width as the equivalent radiating current source described by Eq. (1) becomes larger.

Fig. 4. Simulated (\(\lambda = 1550\) nm) TE mode diameter (FWHM) and TE mode confinement along the a) lateral and b) vertical directions for varying waveguide core widths. The waveguide core thickness is 100 nm for both plots.

Though the lowest scattering loss is achieved in the squeezed out mode regime of Fig. 4, the low confinement of such a waveguide limits its application to very large bend radii or...
efficient fiber-coupling spot-size-converters. Since a waveguide bend is a necessary component of any PIC, a trade-off between low scattering and a practical bend radius must be made. From Fig. 3 and Fig. 4, it can be seen that increasing the core width increases mode confinement and scattering loss from the top and bottom interfaces while also decreasing scattering loss from the sidewall interfaces. For planar waveguides, the $\sigma_{\text{sidewall}}^2$ due to an optimized dry etching of the core is typically around 10 nm$^2$ [15] while the $\sigma_{\text{top/bottom}}^2$ resulting from a polished deposited material is less than 0.1 nm$^2$. Therefore, decreasing $\Pi_{\text{sidewall}}$ at the cost of an increase in $\Pi_{\text{top/bottom}}$ will yield a decrease in total scattering loss up until sidewall scattering loss no longer dominates, that is, until $\Pi_{\text{top/bottom}}$ is greater than $\Pi_{\text{sidewall}}$ by about three orders of magnitude. This implies that the lowest loss Si$_3$N$_4$ core geometry for a given bend radius has the highest single-mode aspect ratio that can maintain low loss around a bend.

For the Si$_3$N$_4$-core waveguide fabrication run characterized in the next section of this paper, a minimum bend radius of 2 mm was chosen in order to fit the desired number of devices onto a single wafer. The run consisted of three core thicknesses. From our bend loss model, we determined that an 80 nm thick waveguide should not be bend loss limited at a bend radius of 2 mm. Therefore 80, 90, and 100 nm core thicknesses were targeted. To ensure single-mode operation in the 100 nm thick waveguides, a maximum waveguide width of 2.8 μm was used on the mask.

3. Waveguide loss characterization

Waveguide loss is often measured using cut-back and Fabry-Pérot resonator (Hakki-Paoli) techniques. For propagation losses on the order of 1 dB/m, cut-back structures must be multiple meters in length to allow for several detectable reductions in propagation loss. For a cut-back waveguide length difference of 1 m, the difference in output power is then also on the order of 1 dB, a value that does not far exceed the typical measurement error, e.g. due to a variance in coupling losses. Thus, long waveguide lengths or a large number of waveguide measurements are necessary to achieve sufficient accuracy. Likewise, the dependence of Fabry-Pérot resonator measurements on the waveguide facet power reflection coefficient can yield a measurement uncertainty on the same order as the total propagation loss in ultra-low-loss waveguides (a few dB). The measurement accuracy can be improved through careful facet preparation or by increasing the sample size of measured data, but both increase the measurement turnaround time. This is a particularly costly outcome if measurement results are to be used as part of a process or design optimization cycle where frequent and immediate feedback is desired.

3.1 Ring resonator measurements

As demonstrated in [7], ring resonators are suitable for measuring ultra-low propagation losses less than 1 dB/m. They also yield propagation loss for a fixed bend radius, clearly showing the bending capabilities of a given waveguide structure. Since the waveguide facets are not part of the resonator being characterized, the measurement is independent of the facet power reflection coefficient and fiber-waveguide coupling loss, avoiding the abovementioned difficulties. In this technique, the output power transmission spectrum of a ring resonator is fit to an (N+1) parameter model where N is the number of waveguides coupled to the ring. If a single waveguide with input and output ports is used, as is the case in this paper, the fit parameters are the round-trip loss of the resonator, $\gamma_0$, and the power coupling ratio of the straight-to-bent waveguide coupler, $\kappa$:

$$\frac{P_{\text{out}}}{P_{\text{in}}} = \left(\frac{\gamma_0 - \kappa}{2T} + j(\omega - \omega_0)\right)^2,$$

where $\omega_0$ is the resonant radial frequency and $T$ is the round-trip time of the cavity. In order to obtain spectra with clear drops in output power at the resonant frequency, the resonators
should be designed such that $\gamma_0$ and $\kappa$ are on the same order. Since $\kappa$ depends primarily on the coupling gap, $w_{\text{gap}}$, between the straight waveguide and ring, it is controlled lithographically. As $\frac{d\kappa}{dw_{\text{gap}}}$ decreases exponentially with increasing $w_{\text{gap}}$, a larger $w_{\text{gap}}$ increases the fabrication tolerance for the measurement structures. For the ring resonator measurement results shown in Fig. 5, a $\kappa$ of $\sim 0.01$ was targeted with a $w_{\text{gap}} \sim 2 \mu$m. By measuring similar ring resonators (same $\gamma_0$) with varying $\kappa$, the measurement accuracy is further improved.

In this work, ring resonators with 0.5, 1, 1.5, 2, and 4 mm radii are characterized. The spectra are obtained from the power transmission of the TE mode excited by a wavelength tunable laser with 100 kHz linewidth. By introducing this frequency resolution into the model given in Eq. (9), we confirm that a propagation loss on the order of 0.1 dB/m can be measured before the frequency granularity introduces a fit value error within an order of magnitude of the loss. Each ring has a single two-port coupling waveguide, and three power coupling ratios are achieved by curving this waveguide around the ring in order to change the length of the coupling region. The loss results from ring resonator measurements are shown in Fig. 5 along with a fit to these results using the loss model fitting parameters, $\sigma_{\text{sidewall}}$ and $\sigma_{\text{surface}}$. For the fit, typical sidewall and surface roughness correlation lengths are assumed. The fit yields roughness parameters $(\sigma_{\text{sidewall}}, L_c) = (14 \text{ nm}, 50 \text{ nm})$ and $(\sigma_{\text{surface}}, L_c) = (0.1 \text{ nm}, 30 \text{ nm})$. At a bend radius of 2 mm, the loss of each core thickness has reached its minimum, indicating that bend radiation loss is negligible for a bend radius greater than or equal to 2 mm as predicted by the bend loss model.

### 3.2 Reflectometry measurements

With optical reflectometry, one can measure the magnitude of the optical power backscattered from a propagation distance, $W_0$, within a waveguide. Assuming a uniform waveguide that is invariant in the propagation direction, the amount of power backscattered from $W_0$ is directly proportional to the amount of power present at $W_0$, and the return loss amplitude is given by [22]:

$$RL(z) = 10\log\left(\frac{P_{\text{backscattered}}(z)}{P_m}\right) = 10\log\left[S\alpha_rw_w\exp(-2\alpha z)\right],$$

where $S$ is the fraction of reflected power captured by the waveguide, $\alpha_R$ is the backscatter loss coefficient, $W_0$ is the spatial resolution of the reflectometry instrument, and $\alpha$ is the power attenuation coefficient of the propagating mode. The propagation loss of the waveguide can then be calculated by taking half of the slope in return loss with respect to distance. As
with ring resonators, the accuracy of a reflectometry measurement is independent of any variance in coupling loss or facet reflectivity. In Fig. 6, the large spikes in measured return loss amplitude demonstrate how reflectometry “sees” large scattering points in the optical path, allowing for the quantification of loss due to point defects separate from the distributed waveguide propagation losses.

In order to verify the ring resonator results, optical frequency domain reflectometry (Luna OBR 4400) is used to measure the propagation loss in 6 meters of spiraled waveguide. The spirals have a minimum bend radius of 2 mm at the S-bend in the center, so the bend loss is expected to be negligible for all waveguide thicknesses. The measured loss should then agree with the minimum loss measured with ring resonators at each thickness. Figure 6 shows the return loss amplitude versus length for an 80 nm thick waveguide spiral. The large spikes in return loss amplitude occur at the fiber-connector and fiber-waveguide interfaces. Index matching gel is used to reduce the reflection at the waveguide’s input facet, and a polarization controller is employed in order to excite primarily the TE mode of the waveguide.

In OFDR, time domain return loss data is extracted from frequency domain data via a Fourier transform, and the spatial domain is then obtained using the group index of the propagating mode. The group velocity can be extracted by dividing the designed waveguide length by the measured delay between the input and output reflections in Fig. 6. This method yields group indices of 1.54, 1.57, and 1.59 for 80, 90, and 100 nm core thicknesses, respectively. These agree well with the group indices of 1.53, 1.55, and 1.57 simulated with PhotonDesign’s FIMMWAVE software. In agreement with the ring resonator findings, linear fits of the OFDR return loss measurements give propagation losses of 2.91 ±0.01, 4.22 ±0.01, and 5.33 ±0.01 dB/m for the 80, 90, and 100 nm thick waveguides.

4. Comparison with state-of-the-art

Figure 7 shows the result of a thorough literature search for state-of-the-art propagation loss reported at a given bend radius in planar single-mode waveguides. Propagation loss values for silicon oxynitride, silicon nitride, Ge-doped SiO$_2$, P-doped SiO$_2$, and polymer waveguide cores are shown as red squares in the figure with index contrasts ranging from 0.25 to 25% [1,6,7,11,22–32]. For completeness, points are included for a typical silicon-on-insulator rib waveguide fabricated at UCSB, as well as the quasi-single-mode NTT result [8]. The Si$_3$N$_4$ core results reported in this paper are marked with blue triangles. To the best of our knowledge, the observed propagation loss of 8.9 dB/m at a 0.5 mm bend radius and for a 100 nm core thickness is ~90 dB/m lower than the previous lowest value reported for waveguides at that radius [11]. The 3 dB/m propagation loss measured at a 2 mm bend radius for an 80 nm
core thickness is 2 dB/m lower than the previous lowest value obtained with lower index contrast waveguides [1,6]. Furthermore, the results reported here fall on the leading edge of a loss-versus-radius boundary along which loss increases with decreasing bend radius. As one pursues smaller bend radii, tighter mode confinement is required, and larger core dimensions or higher refractive index contrasts are employed. This in turn increases the scattering loss of the waveguide assuming no improvement upon the typical roughness parameters obtainable with current fabrication technology.

Fig. 7. A comparison of the high-aspect-ratio Si₃N₄-core loss results (blue triangles) with the state-of-the-art (red squares) [1,6,7,11,22–32]. Dashed lines show the minimum achievable loss at a given bend radius for Si₃N₄-core waveguides from the loss model using current (σ_sidewall = 14 nm) and state-of-the-art (σ_sidewall = 3.16 nm) roughness parameters.

The dashed lines in Fig. 7 show simulation results obtained from our loss model for Si₃N₄-core waveguides. The green (higher loss) curve shows the minimum achievable loss at a given bend radius using the already achieved roughness parameters of (σ_sidewall, L_c) = (14 nm, 50 nm) and (σ_surface, L_c) = (0.1 nm, 30 nm). The good fit of this line with measured waveguide loss suggests the valid exclusion of material absorption loss in our model for that regime. With a loss of ~17 dB/m at 0.2 mm down to ~1 dB/m at 10 mm, the loss model predicts record low loss for single-mode waveguides using the stoichiometric Si₃N₄ technology across the 0.2 – 10 mm bend radius regime. The black (lower loss) line shows the minimum achievable loss at a given bend radius if the mean deviation of the sidewall, σ_sidewall, is reduced to 3.16 nm. This value is reported in [15] as typical for an optimized etch process performed in a state-of-the-art fabrication facility. Additional loss measurements of lower confinement waveguides are necessary to confirm the valid exclusion of material absorption loss in our model for this regime.

Each point on the simulated loss vs. bend radius curves corresponds to the lowest-loss core geometry at that bend radius. Figure 8 shows how the lowest-loss core thickness and width change with increasing bend radius. As larger bend radii are used, lower confinement and higher-aspect-ratio waveguide cores yield the lowest achievable loss. From Fig. 7 and Fig. 8, propagation loss on the order of 0.1 dB/m can be achieved with stoichiometric LPCVD Si₃N₄ by increasing the aspect ratio of the waveguide core, using a larger minimum bend radius of 7 mm, and decreasing σ_sidewall to ~3.1 nm through further optimization of the lithography and sidewall etch processes.
5. Conclusions

An ultra-low-loss planar waveguide technology is demonstrated to bring the performance advantages of optical fiber-based devices to the chip scale. Although several low-index-contrast (Δn = 0.5 – 2.5%) technologies are also good ultra-low loss candidates, stoichiometric LPCVD Si₃N₄, with an index contrast of ~25%, offers the additional benefits of increased material uniformity and stability. Using a high-aspect-ratio core geometry, ultra-low loss can be obtained in single-mode Si₃N₄ waveguides at bend radii as low as 0.2 mm. In this work, we demonstrate record low losses of 8-9, 5, 3.5, and 3 dB/m at 0.5, 1, 1.5, and 2 mm bend radii, respectively. The challenge of measuring ultra-low loss with sufficient accuracy at chip-scale propagation lengths is met using ring resonator and OFDR techniques.

Acknowledgements

The authors thank Scott Rodgers and Wenzao Li for helpful discussions. This work is supported by DARPA MTO under iPhoD contract No: HR0011-09-C-0123.