An ultracompact tapered coupler, which is suitable for mode transformation between a 220 nm high silicon wire waveguide and a Si/III–V hybrid waveguide, is proposed for Si/III–V heterogeneous integration. The tapered coupler is composed of three sections. Since the tapered coupler avoids exciting the unwanted high-order modes in the III–V waveguide, the length of the tapered coupler can be dramatically shortened. In the proposed structure, the total length of the trisectional tapered coupler can be as short as 8 μm with a fundamental mode-coupling efficiency of over 95% in a bandwidth of over 100 nm. The alignment tolerance of the proposed structure is also analyzed.

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1. INTRODUCTION

Photons based on Si/III–V heterogeneous integration through the divinylsilsloxane bis-benzocyclobutene (DVS-BCB) adhesive wafer bonding method or the molecular direct wafer bonding method [1,2] have been introduced and investigated for many applications (e.g., interchip optical interconnects [1,2] and free-space optical communication links [3]), due to its feasibility in combining active and passive photonic submodules onto one silicon substrate. Among various Si/III–V heterogeneously integrated devices, a common critical issue is how to design a compact mode coupler structure to route light efficiently between the III–V active waveguide and the silicon waveguide. A tapered coupler has been considered to be a promising structure for a mode converter due to its low insertion loss, low reflection losses [4], and good fabrication tolerance [5,6].

A shorter tapered coupler can improve the integration density of Si/III–V heterogeneously integrated devices. One way to reduce the taper length is to use a multistep or complex shape tapered structure in both the silicon waveguide and the III–V waveguide [5,6]. Another way is to use a multilevel tapered coupler [4]. These tapered couplers have good fabrication tolerance and have been widely used in hybrid lasers [1], detectors [1], and modulators [7]. However, there are several difficulties in designing an ultrashort tapered coupler. For example, when the tapered coupler is shortened, the high-order modes in the III–V waveguide will degenerate the fundamental coupling efficiency.

In this article, we propose a tapered coupler to overcome the difficulties. The tapered coupler consists of three independent sections. The first section is a vertical coupler for light coupling from the silicon waveguide to a III–V waveguide without the p-InP layer. The second section is a taper for light coupling to a wider III–V waveguide without the p-InP layer. The third section is a taper for light transferring to the III–V waveguide with the p-InP layer. First, we can design each short taper section separately and then combine them together. As a semi-three-dimensional (3D) taper, the proposed trisectional tapered coupler avoids exciting high-order modes in the III–V waveguide. In this way, the total taper length can be 8 μm even when the thickness of the intermediate bonding layer is 50 nm. We also study how the thickness of the layer and the misalignment of each layer influence the performance of the proposed trisectional tapered coupler.

2. DESIGN OF THE TRISECTIONAL TAPERED COUPLER

Figure 1(a) shows the cross section of the Si/III–V hybrid waveguide. The thickness and refractive index in each layer are adopted from [6] and listed in Table 1. The distance between

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the top of the silicon structure and the bottom of the III–V structure is defined as the bonding layer thickness ($h_{\text{BCB}}$). Figures 1(b) and 1(c) show a schematic structure of the proposed trisectional tapered coupler. In the first section, the optical modes are converted from the silicon waveguide to the 0.44 $\mu$m thick III–V waveguide, including the n-SCH (SCH: spatial confinement heter) layer, the multiple quantum well (MQW) layer, and the p-SCH layer without the thick p-InP layer. In the second section, the light transforms into a wider 0.44 $\mu$m thick III–V waveguide to increase the confinement factor in the MQW layer. At the end of the second coupler, the optical mode is already well-matched with the final optical mode of the final Si/III–V hybrid waveguide. Thus, in the third coupler where the thick p-InP layer is tapered, the length can also be short.

The mode coupling between two vertical separated waveguides has been theoretically studied in [8]. The effective mode indices of the two single waveguides will intersect in the coupling structure. Thus, the energy will transfer between these two waveguides. There, it is assumed that each waveguide only supports the fundamental mode. However, in the III–V waveguides as discussed here, lots of high-order modes exist. If effective mode indices of the high-order modes would intersect with that of the silicon waveguide, it is possible that partial energy will couple to the high-order modes of the III–V waveguide.

Due to the fundamental mode input through the silicon waveguide and the symmetry of the system, the excited modes in the tapered section should be only even symmetric along the y axis (assuming no misalignment) [9]. Figure 2(a) shows the effective mode indices ($n_{\text{eff}}$) for different even symmetric modes by varying the width ($W_{\text{III–V}}$) in a conventional configuration of the III–V waveguide where a thick p-InP layer is present. We can see that the III–V waveguide supports lots of high-order modes. On the other hand, a III–V waveguide without the p-InP layer supports fewer modes as shown in Fig. 2(b). What is more, from Fig. 2(b), we can see that the difference between the effective index of the fundamental mode and those of the high-order modes is larger than that shown in Fig. 2(a). In this case, the high-order modes have little influence on the fundamental mode coupling in the tapered sections. Thus, by using a vertical tapered coupler without the p-InP layer in the III–V waveguide we should be able to construct a more compact taper. The present trisectional taper not only induces low reflection, similar to multilevel tapered couplers [4], but also suppresses the high-order modes excited in the first vertical tapered coupler section. By dividing the whole taper structure into three individual sections, the optimization on each section can be done separately, which will be discussed in the following parts of the paper.

The trisectional tapered coupler can be fabricated by using a selective wet etching process, which has been used to fabricate multilevel tapered structures [4]. Figure 3 shows the detail

<table>
<thead>
<tr>
<th>Layer</th>
<th>Thickness ($\mu$m)</th>
<th>Refractive index</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO$_2$</td>
<td>1</td>
<td>1.45</td>
</tr>
<tr>
<td>Si</td>
<td>0.22</td>
<td>3.477</td>
</tr>
<tr>
<td>n-InP</td>
<td>0.14</td>
<td>3.17</td>
</tr>
<tr>
<td>n-SCH</td>
<td>3.46</td>
<td>3.46</td>
</tr>
<tr>
<td>MQW</td>
<td>0.1</td>
<td>3.52</td>
</tr>
<tr>
<td>p-SCH</td>
<td>0.08</td>
<td>3.46</td>
</tr>
<tr>
<td>p-InP</td>
<td>1.5</td>
<td>3.17</td>
</tr>
<tr>
<td>DVS-BCB</td>
<td>-</td>
<td>1.543</td>
</tr>
</tbody>
</table>

Table 1. Specifications for the Thickness and Refractive Index in Each Layer
structural parameters definition. The width of the taper tip ($W_{\text{tip}}$) is limited by the fabrication process. A smaller tip will have less reflection loss. Here we choose $W_{\text{tip}} = 0.15 \, \mu\text{m}$ [6]. The widths of input silicon waveguide is 0.6 $\mu\text{m}$. The width of the MQW layer ($W_{\text{mqw2}}$), SCH layers, and $p$-InP layer ($W_{\text{planp}}$) in the final hybrid Si/III–V waveguide are the same in the design. The $W_{\text{mqw2}}$ is optimized according to optical confinement in the MQW layer. Figure 4 shows the optical confinement factor in the 100 nm thick MQW layer as $W_{\text{mqw2}}$ varies. One can see that the confinement factor becomes stable when $W_{\text{mqw2}}$ is larger than 0.5 $\mu\text{m}$. In the present design, $W_{\text{mqw2}}$ is chosen to be 1.0 $\mu\text{m}$, which falls within the stable region shown in Fig. 4 and is also within the resolution limit of common contact lithography technology. The corresponding confinement factor is $\sim$25%.

In each taper section, we use an exponential shape [6] for each layer. The exponential shape can be defined by four parameters [6]: the width of the input waveguide, the width of the output waveguide, the exponent ($\alpha$), and the length of the taper. During the fabrication, the SCH layers and the MQW layer cannot be selective etched, so they always have the same shape in the design. For simplicity, the exponents of the MQW layer and the thin $n$-InP layers are chosen to be the same in each taper section in the following optimization.

In the first vertical tapered coupler section, we optimize the width of the MQW layer at the end of the taper first. The value of $W_{\text{mqw1}}$ is chosen to be 0.5 $\mu\text{m}$. In this case, the difference of $n_{\text{eff}}$ between the fundamental mode and that of the high-order modes in the III–V waveguide is the largest according to Fig. 2(b). The thin $n$-InP layer has little effect on the mode transformation. In the present example, we choose the width of $n$-InP at the end of the first taper ($W_{\text{planp1}}$) to be 1.5 $\mu\text{m}$, which can be considered wide enough for the fundamental mode. However, there are still three parameters that need to be studied and optimized in the first section, namely the length of the taper $L_1$, the exponent $\alpha_3$ of silicon waveguide, and the exponent $\alpha_1$ of the III–V waveguide.

In the second tapered coupler section, $W_{\text{mqw2}}$ is 1 $\mu\text{m}$, which is the width of the final III–V waveguide. In the present example, the width of $n$-InP at the end of the second taper ($W_{\text{planp2}}$) is further expanded to 3 $\mu\text{m}$. There are two parameters that need to be optimized in this section, namely, the length of the taper $L_2$ and the exponent $\alpha_2$ of the III–V waveguide.

In the third tapered coupler section, $W_{\text{planp}}$ is set to be 1 $\mu\text{m}$, the same as the width of the MQW layer, which is nonvariant in this section. The length of the taper $L_3$, and the exponent $\alpha_3$ of the $p$-InP layer needs to be optimized.

### 3. DESIGN RESULTS

We use a 3D finite-difference time-domain method [10] to simulate the optical performance of each section. Each section is optimized separately to achieve a high fundamental mode coupling efficiency. Then the three taper sections can be combined together to form the whole structure. As a design example, we set $h_{\text{BCB}} = 50$ nm, which is a typical value in the BCB bonding technology [11]. The corresponding parameters mentioned in the previous section are swept, and the results are shown in Fig. 5. One can find that the exponent of the silicon waveguide ($\alpha_3$) does not pose a noticeable influence on the coupling efficiency while other exponents ($\alpha_1$, $\alpha_2$, and $\alpha_3$) do have optimal values where the coupling efficiency reaches maximal. Thus, $\alpha_3 = 2.2$, $\alpha_1 = 0.6$, $\alpha_2 = 0.6$, and $\alpha_4 = 0.9$ are chosen according to Figs. 5(a)–5(c). On the other hand, the taper lengths have to be long enough. As shown in Figs. 5(d)–5(f), $L_1 = 4$ $\mu\text{m}$, $L_2 = 1$ $\mu\text{m}$, and $L_3 = 3$ $\mu\text{m}$ are adopted. Beyond these values, the coupling efficiencies remain over 96% and within a fluctuation of less than 3%. This ensures an adiabatic behavior for each taper section. The total length of the tapered structure is therefore 8 $\mu\text{m}$.

Figure 6 shows the simulation results of the whole tapered coupler. As shown in Fig. 6(a), the overall fundamental mode coupling efficiency is over 95% and 90% in a wavelength range over 100 and 300 nm, respectively. From Fig. 6(a), one can also see that in the short wavelength region the coupling efficiency is mainly limited by the first section taper, while in the long wavelength region, the coupling loss in the third taper becomes dominant. In Fig. 6(b), we also analyze the taper performance with different $h_{\text{BCB}}$, since $h_{\text{BCB}}$ can vary in different fabrication runs. Figure 6(b) indicates that this 8 $\mu\text{m}$ long tapered coupler can also have a coupling efficiency of over 90% when $h_{\text{BCB}}$ varies from 20 to 80 nm. Figure 6(c) shows the field distribution of the light propagation from the silicon waveguide to the III–V waveguide at 1.55 $\mu\text{m}$ with $h_{\text{BCB}} = 50$ nm. In general, light coupling between the two waveguides occurs mainly at the first taper section. Therefore, the performance of the first taper

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**Fig. 3.** Detail structure parameters for the trisectional tapered coupler. (a) First section by a vertical tapered coupler. (b) Second taper. (c) Third taper.

**Fig. 4.** Confinement factor in the 100 nm thick MQW layer.
would be sensitive to the bonding layer thickness. After the light transferred to the III–V waveguide, the bonding layer will have little impact on the second and the third tapered couplers. This complies with the results shown in Fig. 6(c).

Three mask alignment processes are needed to define the proposed trisectional tapered coupler. They are for the \( p \)-InP layer, the MQW layer and SCH layers, and the \( n \)-InP layer. Here, we further analyze the influence of the misalignment of each mask on the coupling efficiency. From Fig. 7(a), one can see that the misalignment of the \( p \)-InP layer only affects the coupling efficiency in the third section, which is an intuitive result since the \( p \)-InP layer only exists in the third taper. From Fig. 7(b), one can see that the misalignment of the MQW layer and \( n(p) \)-SCH layer affects the performance of both the third section and the first section and has the largest influence on the overall coupling efficiency among all the misalignments. From Fig. 7(c), one can see that misalignment of the \( n \)-InP layer has very little impact on the overall taper coupling efficiency. Based on the above analyses, in order to keep the coupling efficiency of this 8 \( \mu \)m long taper over 90%, the misalignment of the MQW layer and SCH layers should be within \( \pm 100 \) nm.

In order to increase the bandwidth and the fabrication tolerance of the bonding layer thickness and the mask misalignments, the performance of the first and third taper sections needs to be improved. One simple way is to increase the length of these sections. We further increase \( L_1 \) to 8 \( \mu \)m and \( L_3 \) to 5 \( \mu \)m and keep other structural parameters the same. The total taper length is then increased to 14 \( \mu \)m. The simulation results of this elongated tapered coupler are shown in Fig. 8.

As shown in Fig. 8(a), the overall fundamental mode coupling efficiency is over 95% and 90% within a larger wavelength range of over 200 and 500 nm, respectively. Figure 8(b) indicates that the coupling efficiency stays above 95% when \( h_{BCB} \) varies from 0 to 100 nm. Figure 8(c) also shows the field distribution of the light propagation from the silicon waveguide to the III–V waveguide through this 14 \( \mu \)m long tapered coupler at 1.55 \( \mu \)m with \( h_{BCB} = 50 \) nm.

Figure 9 shows how each mask misalignment influences the coupling efficiency in the case of this 14 \( \mu \)m long tapered coupler. A longer taper has better fabrication tolerance on the...
misalignment of each layer as compared to the results shown in Fig. 7. Within ±200 nm misalignment on the \( p \)-InP layer, ±100 nm misalignment on the MQW and SCH layers, and ±150 nm misalignment on the \( n \)-InP layer, the overall coupling efficiency of this taper remains above 95%. From the above discussions, it can be concluded that the second mask alignment (for fabricating the MQW and SCH layers) is the most important fabrication step for a high coupling efficiency tapered coupler.

Normally, it is not critical for hybrid modulators [7] to have a very high coupling efficiency as compared to hybrid lasers [1,12] or amplifiers [12]. In order to keep the driving speed high, a shorter device is more desirable. Thus, the 8 μm long tapered coupler is more suitable for hybrid modulators. On the other hand, the 14 μm long tapered coupler is more suitable for hybrid lasers or amplifiers, where coupling losses are more critical. For a hybrid laser structure, the interband absorption of the unpumped quantum wells might be a problem in a III–V taper without the \( p \)-InP layer [4]. However, in the proposed mode coupler, this taper section is kept very short. The total area of the unpumped quantum wells is only about 8%–4% of the pumped ones in the actual amplifier section (considering the length of the final hybrid waveguide is about 200–400 μm [1]). It can be considered as a short saturation-absorber [13], which will not degrade the laser performance significantly. This issue also exists in the conventional taper design with the \( p \)-InP layer in the whole taper section, since the high contact resistance of the \( p \)-metal and the high lateral resistance of the \( p \)-cladding layer will prevent an efficient pumping of the
4. CONCLUSION

In this paper, an ultracompact coupler has been proposed by using a trisectional tapered structure to transform the light between a silicon wire waveguide of 220 nm height and a Si/III–V hybrid waveguide with the DVS-BCB adhesive bonding technology. Eliminating the thick p-InP layer in the first taper section avoids exciting high-order modes and decreases the coupler length. The other two sections reduce the mode mismatch and couple the light into the final hybrid waveguide. In this way, a coupling efficiency of over 95% can be achieved in a wavelength range of ∼100 nm even when the total taper length is only 8 μm. Our simulations have also shown that the mask alignment of the MQW and SCH layers is one of the most important process parameters to the whole taper. We have analyzed the means to improve the fabrication tolerance and the bandwidth of the taper through increasing the length of the first and third sections. We believe the proposed tapered coupler can be used in various Si/III–V heterogeneous integrated devices.

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