Near-field optical storage system using a solid immersion lens with a left-handed material slab

Liu Liu and Sailing He

Centre for Optical and Electromagnetic research, Joint Research Center of Photonics of the Royal Institute of Technology (Sweden) and Zhejiang University, State Key Laboratory for Modern Optical Instrumentation, Zhejiang University, Yu-Quan, Hangzhou, 310027, China; and Laboratory of Photonics and Microwave Engineering, Department of Microelectronics and Information Technology, Royal Institute of Technology, Electrum 229, 16440 Kista, Sweden
sailing@kth.se

Abstract: A new near-field optical storage system utilizing a left-handed material (LHM) is introduced by attaching an LHM slab to the lower surface of a conventional solid immersion lens (SIL). The performance of the present storage system is compared with a conventional SIL system through numerical simulation. The LHM slab in the present storage system can image very well the focused spot at the lower surface of the SIL to the surface of a disc. It allows a large air-gap for the mechanical convenience while keeping a large signal contrast and a high storage density. The tolerance of the air-gap is also improved.

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References and links

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1. Introduction

To increase the storage density, solid immersion lenses (SILs) have been used in optical storage systems by means of increasing the numerical aperture [1]. A schematic diagram of a conventional near-field optical storage system using an SIL is shown in Fig. 1. An aberration-free objective lens focuses a collimated beam onto the SIL. All the rays pass perpendicularly through the upper spherical surface of the SIL without changing their propagation directions. The focal plane lies right on the lower (planar) surface of the SIL. After the interaction between the laser beam and the disc, the reflected beam is collected by the same objective lens and directed to a detector. The detected signals are then decoded to recover the digital information recorded in the disc. The effective numerical aperture (NA_{eff}) of the whole system can be expressed as NA_{eff} = n_S \cdot \sin \theta_m, where n_S is the refractive index of the SIL. The size of the focused spot is proportional to \lambda_0/NA_{eff} (here \lambda_0 is the working wavelength in vacuum).

Thus, to achieve a small focused spot at the lower surface of the SIL, a large NA_{eff} is preferred (usually NA_{eff}>1). However, such a small focused spot can only exist near the SIL-air interface since the high frequency components in the angular spectrum of the focused-beam become exponentially decaying (i.e., the evanescent waves) in the air-gap besides the divergence of the low-frequency components. Therefore, in a conventional SIL system (see the left inset of Fig. 1), the laser beam diverges very fast in the air-gap. Thus, in order to achieve a large signal contrast and a high storage density, the disc should always be placed very close to the lower surface of the SIL (usually the air-gap \( h_a \) is smaller than 100nm). This will bring some mechanical difficulty/inconvenience of the storage system. Many efforts have been made to increase the air-gap while keeping the signal contrast and the storage density at an acceptable level. Milster et al. [2] showed that the signal contrast can be improved by placing a pupil filter in front of the SIL. Hirota et al. [3] filled the air-gap with a liquid lubricant to increase the total internal refraction angle at the lower interface of the SIL. Liu et al. [4] increased the focal depth of an SIL with an annular aperture in front of the SIL. In all these approaches, the smallest beam spot of the whole system is still located at the lower surface of the SIL.

![Fig. 1. Schematic diagram of the near-field optical storage system using an SIL.](image-url)
resolution [6]. However, some intrinsic aspects (such as the losses [7, 8] and the finite lateral size [9]) will degrade the image quality. Nevertheless, subwavelength imaging/focusing can still be achieved for a thin LHM slab [10]. In the present paper, we introduce a new near-field optical storage system by attaching an LHM slab to the lower surface of the SIL (hereafter we refer to this system as an L-SIL system; see the right inset of Fig. 1).

2. The new storage system with an LHM slab and numerical simulation

In the present L-SIL system, the focused spot at the lower interface of the SIL can be imaged to the surface of the disc with subwavelength resolution since the high frequency (i.e., evanescent) components in the angular spectrum of the focused beam can be amplified in the LHM slab [6]. The quality of the imaged focused spot could be excellent if one matches the parameters of the LHM slab to those of the air-gap by setting $h_L = h_a$ and $(\hat{\epsilon}_L, \hat{\mu}_L) = -(\hat{\epsilon}_a, \hat{\mu}_a)$, where $\hat{\epsilon}_L$ ($\hat{\mu}_L$) and $\hat{\epsilon}_a$ ($\hat{\mu}_a$) are the relative permittivity (permeability) of the LHM slab and the air-gap, respectively. The main advantages of the present L-SIL system over the conventional SIL system are: (1) The air-gap of the present L-SIL system can be much larger than that of the conventional SIL system. The collision between the SIL and the disc can then be avoided. Theoretically a larger air-gap in the present L-SIL system will not degrade the signal contrast and the storage density if the above match condition is satisfied. (2) In a conventional SIL system, the detected signal will be very sensitive to a small change of the air-gap (due to the fast decay of the light intensity in the air-gap) and thus an accurate servo system is needed in order to maintain accurately the air-gap [13]. However, in the present L-SIL system the light intensity will not change so fast near the imaged focal plane and thus the tolerance of the air-gap will be improved. Below we will verify these advantages for a two-dimensional (2D) case (for simplicity) with a combined vectorial numerical method [14].

The combined vectorial method is based on a vectorial diffraction formulation [15] (which is used to calculate the propagation of the field between the objective lens and the disc) and a FDTD algorithm [16] (which is used in the near-field calculation). An $x$-polarized Gaussian field is incident on the entrance pupil of the objective lens. The waist radius of the Gaussian field is chosen to be the radius of the aperture. The vectorial diffraction formulation is first used to calculate the distribution of the incident field just above the lower surface of the SIL. This incident field is then used as the source in the 2D FDTD near-field calculation. The entire FDTD computation domain is divided into a total-field region and a scattered-field region by a source plane perpendicular to the $z$ direction, as shown in Fig. 2. The LHM slab, the air-gap and the disc are all located in the total-field region. The computation domain is truncated with a perfectly matched layer (PML; as the boundary treatment). After the FDTD iteration reaches a steady state, the reflected field is extracted by means of the Fourier transform (with respect to the time) at the sampling plane (which lies in the scattered-field region).
region; see Fig. 2). The distribution of the reflected field at the entrance pupil of the objective lens is then calculated by the vectorial diffraction formulation. Finally, the power carried by this reflected field is considered as the detected signal $I$ (normalized with the power of the incident field). To obtain a convergent result at the working frequency with an FDTD algorithm, we choose the following lossy Drude polarization and magnetization model [17] for the relative permittivity and permeability of the LHM slab

$$
\hat{\epsilon}_l(\omega) = 1 - \frac{\omega^2_{pe}}{\omega^2 + j\gamma_e \omega}, \quad \hat{\mu}_l(\omega) = 1 - \frac{\omega^2_{pm}}{\omega^2 + j\gamma_m \omega},
$$

where $\omega$ is the angular frequency, $\gamma_e$ and $\gamma_m$ are the damping coefficients, and $\omega_{pe}$ and $\omega_{pm}$ are the plasma frequencies.

The working wavelength $\lambda_0$ is chosen to be 650nm. The numerical aperture of the objective lens is 0.6 (i.e., $\sin \theta_m = 0.6$). The SIL is made of LaSF9 glass with $n_s = 1.843$ [3]. This will give $\text{NA}_{\text{eff}} = 1.1058$. The refractive index of the air-gap is set to $n_a = 1.0$ (i.e., no liquid lubricant is used). To fulfill the match condition $\hat{\epsilon}_l \cdot \hat{\mu}_l = -\epsilon_0 \mu_0 \omega^2 / \lambda_0^2$ (where $c$ is the light speed in vacuum), the plasma frequencies should satisfy $\omega_{pe}^2 = \omega_{pm}^2$. A low loss is included in the simulation by setting $\gamma_e = \gamma_m = 3 \times 10^{-4} \omega_0$. This will give $\hat{\epsilon}_l = \hat{\mu}_l = -1 + j 6 \times 10^{-4}$ (i.e., both the permittivity and the permeability are dominated by negative real parts at $\omega_0$). Note that the present idea and results at $\omega_0$ have nothing to do with Eq. (1) for the polarization and magnetization model. Equation (1) is adopted in the present paper merely to obtain a convergent FDTD algorithm since unlike for a non-dispersive usual medium a standard FDTD algorithm for a non-dispersive LHM does not converge numerically (see e.g. [9]). A phase-change disc (see Fig. 2) is considered in the simulation. The phase-change layer (GeSbTe) consists of the regions of crystalline state and amorphous state periodically (the period is $T_s$; the spatial frequency $f_s = 1/T_s$ is used in the following analysis). These crystalline and amorphous states (which are often called information pits) correspond to the digital information stored in the disc. The structural parameters are also indicated in Fig. 2. The focused spot is scanned along one direction (the $y$ direction). Due to the different reflection coefficients of the crystalline and amorphous states, the detected signal will vary at different locations of the focused spot. The detected signal is usually at a maximal/minimal value when the focused spot is located at the center of the crystalline or amorphous region (which is denoted by $I_x$ or $I_a$). The signal contrast $V$ is defined as $V = |I_x - I_a| / (I_x + I_a)$. To ensure a large signal-to-noise ratio (SNR), a large $V$ is always preferred.
3. Numerical analysis

Figure 3 shows the near-field distributions in the absence of disc. In the conventional SIL system, the field diverges very fast when it leaves the SIL-air interface (we refer to Ref. [18] for a detailed analysis of the spot-size performance for a conventional SIL system). However, in the present L-SIL system the field becomes convergent at the LHM-air interface, and a focused spot is formed at the air-gap (700nm away from the LHM-air interface; see Fig. 3(b)). This focused spot can be seen as the image of the beam spot at the lower interface of the SIL. The field distributions of these two spots along the y direction are shown in Fig. 3(c), from which one sees that the imaged focused spot is widened a bit and its peak amplitude decreases a bit. This is due to the small loss of the LHM slab [7, 8].

![Graph](image)

Fig. 4. The detected signals $I_x$ and $I_a$, and the signal contrast $V$ as the air-gap increases in (a) the conventional SIL system and (b) the present L-SIL system (with $h_L=h_a$). The spatial frequency $f_s=0$.

![Graph](image)

Fig. 5. Dependence of the normalized signal contrast on the spatial frequency $f_s$ for different values of air-gap $h_a$ in (a) the conventional SIL system and (b) the present L-SIL system (with $h_L=h_a$).

Figure 4 shows the detected signals $I_x$ and $I_a$, and the signal contrast $V$ as the air-gap increases in the conventional SIL system and the present L-SIL system when the phase-change layer is uniform with the crystalline or amorphous state (i.e., the spatial frequency $f_s=0$). One sees that in the conventional SIL system the signal contrast $V$ falls down quickly when $h_a$ increases from 0 to about 200nm, and then becomes oscillating with a damped amplitude when $h_a$ increases further. However, in the present L-SIL system, $V$ is nearly constant when the air-gap varies (with $h_L=h_a$). A practical optical disc will contain information pits with different spatial frequencies $f_s$. Figure 5 shows the dependence of the signal contrast $V$ (normalized with its value at $f_s=0$ for each curve) on the spatial frequency $f_s$ for different values of the air-gap in the conventional SIL system and the present L-SIL system. Each curve in Fig. 5 gives the response of a low frequency filter. The pass-band width of the curve...
usually determines the storage density of a disc. From Fig. 5(a) one can clearly see that the pass-band width of the conventional SIL system becomes very narrow when the air-gap $h_a$ increases to 700nm. Taking both the signal contrast (cf. Fig. 4(a)) and the storage density (cf. Fig. 5(a)) into consideration, the air-gap in the conventional SIL system should be very small (e.g. less than 100nm). However, in the present L-SIL system, the pass-band width for $h_a=700$nm decreases only a little as compared with that for $h_a=50$nm (see Fig. 5(b)).

From the above analysis, we can conclude that the air-gap in the present L-SIL system can be much larger (for the mechanical convenience) than that in a conventional SIL system, while keeping a large signal contrast and a high storage density. The above analysis is based on the assumption of $h_a=h_L$. In a practical system, it is difficult to adjust the air-gap precisely to the thickness of the LHM slab dynamically during the readout process. Thus, it is necessary to analyze how the signal contrast varies when the air-gap $h_a$ has a small variation around the designed value $h_a=h_L$ in the present L-SIL system. The tolerances of the air-gap for the conventional SIL system with $h_a=50$nm and the present L-SIL system with $h_a=h_L=700$nm are shown in Fig. 6 (with $f_s=0$). The tolerance of the air-gap can be defined as the air-gap range in which the signal contrast does not vary beyond 10% of its value at the designed air-gap. The signal contrast $V$ for the conventional SIL system decreases monotonically as the air-gap increases (see Fig. 6). However, for the present L-SIL system, the signal contrast $V$ has a peak at about $h_a=690$nm and $V$ does not change much around this peak. From Fig. 6 one sees that the tolerance of the air-gap increases to about 40nm in the present L-SIL system while the tolerance is only 15nm in the conventional SIL system.

![Fig. 6. The tolerance of the air-gap $h_a$ around the designed value in the conventional SIL system and the present L-SIL system.](image)

### 4. Conclusion

A new setup of a near-field optical storage system has been introduced by attaching an LHM slab to the lower surface of an SIL. The performance of the present L-SIL system has been compared with that of a conventional SIL system. Numerical simulation results have shown that the air-gap in the present L-SIL system can be greatly increased while keeping a large signal contrast and a high storage density if the match condition $[h_L=h_a$ and $(\hat{e}_s,\hat{\mu}_s) = -(\hat{e}_a,\hat{\mu}_a)]$ is satisfied. It has also been shown that the tolerance of the air-gap is improved in the present L-SIL system. These will make the mechanical parts of the storage system much simpler. These advantages of the present L-SIL system can be more significant if a larger NA$_{eff}$ is employed. The present idea can be readily extended from the optical storage to the fields of nanolithography and microscopy, and the LHM slab can also be replaced with another type of subwavelength focusing lens such as a slab of photonic crystal of negative refraction [19].

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