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Improvement of Near-field Optical Storage System with An Artificial Negative Index Film

Taikei Suyama[1], Yaoju Zhang [2], Shi Bai[1], Yoichi Okuno[1]
[1] Graduate School of Science and Technology, Kumamoto University
2-39-1 Kurokami, Kumamoto 860-8555, Japan, syuu@cs.kumamoto-u.ac.jp
[2] Department of Physics and Electronic Information, Wenzhou University,
Wenzhou 325035, China

1. Introduction

We report a new method of enhancing the intensity of spot and improving the air-gap width of a near-field optical storage system with a real artificial negative index film (NIF). This method is based on surface plasmas excited by NIF combining a polymer film. In 2004, Liu and He proposed a near-field SIL optical storage system utilizing a negative index material [1]. In this paper, we develop the concept of the near-field optical storage using a NIF introduced by Liu and He and propose a new near-field solid immersion lens (SIL) optical recording system. Our method is based on the surface plasmas (SP) excited by a NIF-polymer composite nano-layer which is attached on the plane surface of the SIL. An experimentally-fabricated negative index material comprising silver nanorods [2] is chosen as the NIF and the refractive indices mismatching effect is considered in our simulations. The proposed system may be much more close to an actual near-field optical recording system. Numerical results based on the simple vector diffraction theory show that the present system can reduce energy loss markedly and substantially increase the gap's width of the near-field optical storage system with a SIL.

2. Vector diffraction theory

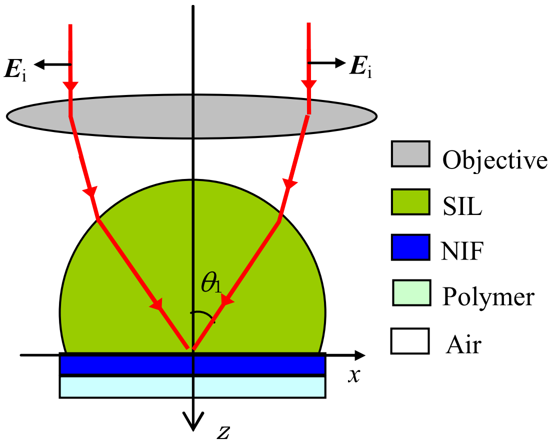


Figure 1 Schematic diagram of the focusing system in the near-field optical storage with an aplanatic solid immersion lens.

Figure 1 shows the schematic diagram of the focusing system in near-field optical storage used in our studies. An aplanatic solid immersion lens [3] is placed in the focal region of the objective and the focus is in the bottom surface of the SIL. The SIL is attached a layer of the negative-index nano-film and then a polymer nano-film is attached on the lower surface of the NIF. This structure is different from that in Ref. [1]. First of all, it is a 3D structure with an aplanatic SIL which can lower the limitation to the objective. Secondly, the NIF is an experimentally-fabricated negative index material and is not an ideal material. The NIF's thickness is in nanometer scale to excite SP and is no any large. Thirdly, a layer of thin polymer film is used to further enhance the SP effect of the nano-NIF, which can be also considered a protecting layer of the NIF. Finally, the system is illuminated by a radially-polarized beam to achieve a small spot. According to the vector diffraction theory presented by Richards and Wolf [4], the electric field distribution near the focus of the lens can be expressed, in the cylindrical coordinates, as [5, 6]

$$\begin{aligned} E_\rho(\rho,z) &= i\int_0^{\theta_{1\max}} t_{sys}^p \cos\theta_4 \sqrt{\cos\theta}\sin\theta_1 l_0(\theta) J_1(k_1\rho\sin\theta_1)\exp[ik_3(z-d-h)\cos\theta_4]\mathrm{d}\theta_1 \\ E_z(\rho,z) &= -\int_0^{\theta_{1\max}} t_{sys}^p \sin\theta_4 \sqrt{\cos\theta}\sin\theta_1 l_0(\theta) J_0(k_1\rho\sin\theta_1)\exp[ik_3(z-d-h)\cos\theta_4]\mathrm{d}\theta_1 \end{aligned}, \quad (1)$$

where $\theta_{1\max} = \arcsin(n_1 \mathrm{NA}_{\mathrm{obj}})$ is the convergence angle related to the numerical aperture ($\mathrm{NA}_{\mathrm{obj}}$) of the objective. $k_i = 2\pi n_i/\lambda$ is the wavenumber in the dielectric i and n_i $(i = 1, 2, 3, 4)$ is the refractive index of the SIL, NIF, polymer, and air, respectively. According to the condition of the aplanatic SIL and Snell's law, we have $\theta = \arcsin(\sin\theta_1/n_1)$ and $\theta_4 = \arcsin(n_1\sin\theta_1/n_4)$. d and h is the thickness of the NIF and polymer films, respectively. J_n is the nth-order Bessel function of the first kind. t_{sys}^p is the effective transmittance complex amplitude coefficient of the system, which can be obtained by using the transfer-matrix method [7]. $l_0(\theta)$ is the relative amplitude of the electric field in front of a pupil. For a radially-polarized beam, $l_0(\theta)$ can be expressed as

$$l_0(\theta) = \frac{\beta_0 \sin\theta}{\mathrm{NA}_{\mathrm{obj}}}\exp\left[-\left(\frac{\beta_0\sin\theta}{\mathrm{NA}_{\mathrm{obj}}}\right)^2\right]. \quad (2)$$

Here β_0 is the size parameter of the incident beam determined by the ratio of the pupil radius to the incident beam waist in front of the objective.

3. Numerical results

In numerical calculations we use following parameters. The wavelength of the incident laser is λ=532 nm. The glass of n_1=2.2 and the polymethyl methacrylate (PMMA) of n_3=1.6 are chosen as the materials of the SIL and polymer films, respectively. The numerical aperture of the objective is $\mathrm{NA}_{\mathrm{obj}}$=0.45 and the size parameter of beam is β_0=1.2 for the focusing system shown in Fig. 1. The NIF's refractive index is chosen to be the experimental values presented by Jen *et al.* [2]: n_2 = -0.705+i1.091 for the TM wave. This NIF material has been fabricated by depositing thin films comprising parallel, tilted silver nanorods on the fused silica substrate and it has the negative refraction effect at visible light frequency band for all angles [2].

3.1 SP excitation

It is seen from Eq. (1) that the transmission field distribution of the system shown in Fig. 1 is related to the system's effective Fresnel coefficient t_{sys}^p. To strengthen the intensity of the transmission field, we apply the SP effect of the NIF-polymer composite layer. The thickness of the NIF-polymer composite layer should be chosen in nanoscale, generally tens of nanometers. Figure 2 shows that the transmission curves of two SIL/NIF/PMMA/air four-layer structures. As comparison, the transmission curve of a bare SIL system (d=h=0) is also compiled together.

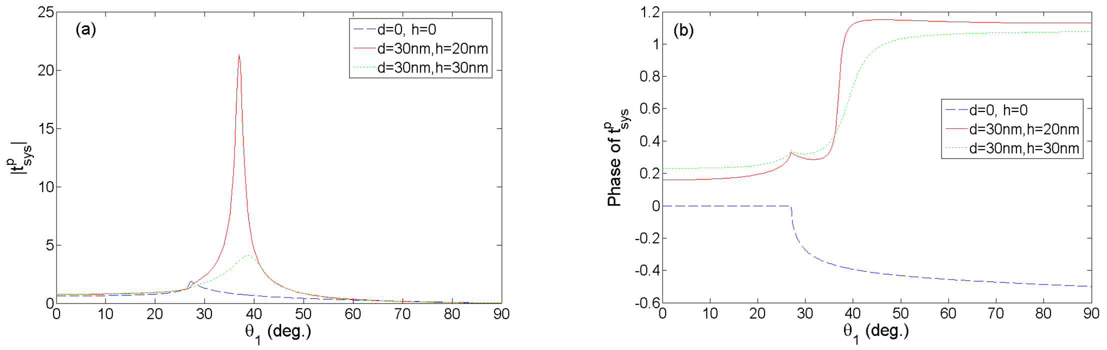
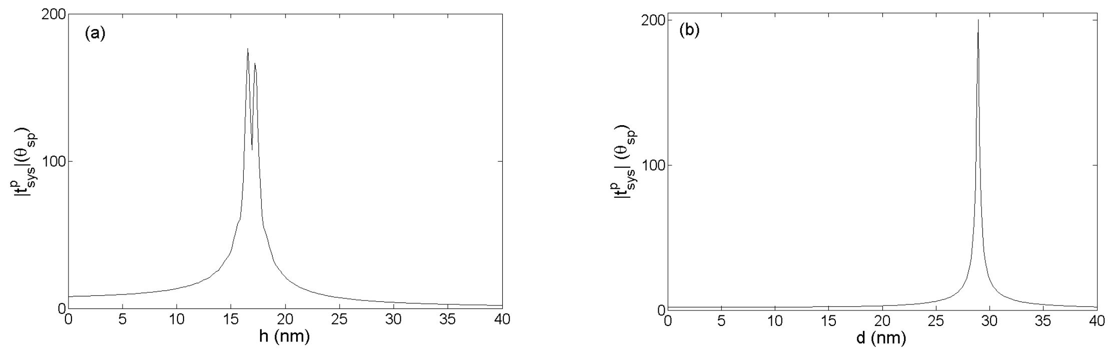


Figure 2 The transmission curves of the SIL/NIF/PMMA/air four-layer structures of (a) amplitude and (b) phase.

In the transmission curves of t^p_{sys} with a NIF- PMMA composite layer, the transmission maximum is the SP excitation position, meaning that the energy of the incident light transfer into the SP energy at this incident angle (the incident angle θ_1 inside the SIL corresponding to the in-plane wavevector $k_1 \sin\theta_1$). At this maximum position, the in-plane wavevector of the incident light is equal to that of the excited SP ($k_{sp} = k_1 \sin\theta_{sp}$, where θ_{sp} is called the SP's characteristic angle). From Fig. 2(a) it is found the transmission intensity of the two four-layer structures near the condition that the SP is excited is much larger than that of a bare SIL, for examples, $|t^p_{sys}|$=21.35 when d=30 nm and h=20 nm, $|t^p_{sys}|$=4.09 when d=30 nm and h=30 nm, but $|t^p_{sys}|$=1.89 when d=h=0. When SP wave passing through these dielectric structures, its phase can be differentially changed (see Fig. 2(b)). Figure 3 (a) and (b) display the dependence of the SP's magnitude on the PMMA's thickness h and on the NIF's thickness d, respectively. It is seen from Fig. 3 that when the PMMA's thickness is in the range of about 10 nm < h < 22 nm and the NIF's thickness is in the range of about 25 nm < d <35 nm, the NIF-PMMA composite layer can excite strong SP, therefore, one should choose the values of h and d within above these ranges to utilize the SP effect as adequately as possible.

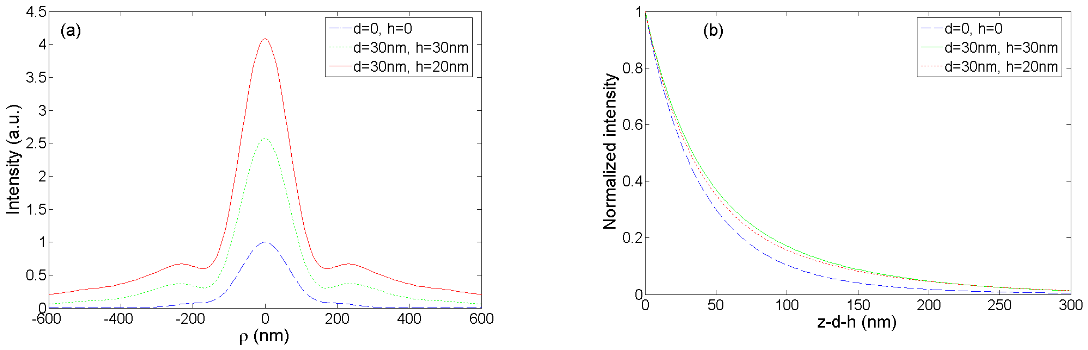


(a) (b)

Figure 3 The SP's magnitude versus h when d=30nm (a) and versus d when h=20nm (b).

3.2 Focused field distribution with a SIL-PMMA composite layer

Figure 4 shows the intensity distributions, in the plane of z_c=d+h, of the focusing system in Fig. 1. All of intensities in Fig. 4(a) are normalized to the center intensity of spot without the NIF-PMMA composite layer. Each intensity in Fig. 4(b) is normalized to its corresponding intensity in the interface of z=d+h. It is obvious that the intensity of spot with a composite layer is much larger than that without a composite layer in Fig. 4(a).



(a) (b)

Figure 4 The intensity distributions in the transverse direction in the plane of $z=d+h$ (a) and along the optical axis (b) for the focusing system with different four-layer structures.

4. Conclusion

A new near-field focusing system has been proposed by attaching a NIF-polymer composite layer to a SIL. Strong surface plasmas effect excited by a real NIF combining a polymer film is used to enhance the transmission of light from the near-field optical storage system with a SIL. This is achieved by recognizing that recently fabricated films comprising metal nanorods have the negative refraction effect at visible light frequency band for all angles [2, 8]. The 3-D field distribution of a near-field optical storage system is calculated using the vector diffraction theory and numerical results show that the intensity of spot and air-gap width, when a properly designed NIF-PMMA composite layer is attached to the SIL, are much larger than those of a conventional near-field optical recording system with a bare SIL, while the size of spot is almost unchanged. The present method can be readily extended from the optical storage to the fields of nanolithography and microscopy.

References

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