Experimental research on high density data storage using solid immersion lens

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We have set up a solid immersion lens (SIL) near-field static recording system for demonstrating preliminarily the feasibility of SIL technology in the higher density storage. The experimental result with recording mark size of 240 nm is obtained corresponding to a potential of density of tens of gigabits per square inch. Some factors in the SIL near-field recording are discussed.

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Near-field optical technology in the field of high-density data storage has attracted much attention from academic community and industry in recent years[1,2]. Near-field optical recording is considered as a kind of promising storage technology in the coming years. It has some advantages, such as higher density, mass storage capacity, and compatible with some well developed technologies. There are mainly four approaches realizing near-field optical recording: near-field optical probe type, solid immersion lens (SIL), super resolution near-field structure (super-RENS), and very small aperture laser (VSAL)[3]. The common performances of them are for decreasing the recording mark size in different ways.

In 1992 Betzig group[4] firstly performed near-field recording on magneto-optical medium using optical probe of near-field scanning optical microscope (NSOM). A recording mark of 60 nm and storage density of 45 Gb/in^2 were obtained. It has some drawbacks although super-resolution mark size and higher density may be realized by the optical probe. The low transmission efficiency, slow feedback rate due to rigorous distance control, and fragility of the probe restrict the application and development of probe-like near-field optical storage technology. The method of SIL was proposed by Kino and Mansfield to improve resolution of optical microscopes[5] and used for optical data storage later[6]. The recording mark size may be decreased by a factor of the refractive index n of the SIL. If the recording medium is placed close enough to the flat surface of SIL, the laser energy may be transferred into the medium layer by near-field optical coupling and sub-wavelength marks may be recorded. In this case the effective numerical aperture (NA) of the focusing lens will be much greater than one. Terris demonstrated a SIL near-field optical recording system and got a recording mark of 350 nm in 1994[7]. Lu achieved 500-nm-diameter recording mark with SIL system based on 532-nm wavelength and azobenzene polymer[8]. The SIL near-field recording can get much higher efficiency than probe and higher resolution than traditional focusing lenses in the pick-up of commercial optical disk drivers.

When a hemispherical SIL is employed, the resolution capacity of the imaging system is expressed as[1]

$$\Delta x = \frac{0.61\lambda_0}{\mathrm{NA_{eff}}} = \frac{0.61\lambda_0}{n_{\mathrm{SIL}}\mathrm{NA}}, \quad (1)$$

where n_{SIL} is the refractive index of the SIL, Δx is the resolution capacity of the imaging system, λ_0 is the wavelength of incident light in vacuum, and NA is the numerical aperture of the objective lens in air.

A static SIL near-field optical recording system has been built in our laboratory. Some experiments have been carried out based on this system. The improvement of recording mark size by SIL is demonstrated experimentally. The influence factors in the SIL near-field recording system are discussed in this paper.

The SIL near-field optical recording static system is depicted in Fig. 1. An Ar^+ laser with the wavelength of 488 nm and the output power of 100 mW is used as the light source. The laser beam passes through a Glan-Taylor prism as a polarizer to generate a high linear polarized beam. Then the beam passes through a polarization beam splitter (PBS) and a quarter wavelength ($\lambda/4$) retardation plate. A readout unit is comprised of the PBS, the $\lambda/4$ plate, and a photo-detector. After reflected by a mirror, the beam is expanded by a telescope with a spatial filter to reduce aberrations and collimate the beam to get the homogeneous intensity distribution. A portion of collimating beam is reflected by a beam splitter and focused by an objective on the bottom surface of the SIL to form spot beyond the diffraction limit. The reflected light from the recording medium can be collected by the SIL, the objective lens, and a photo-detector or observed

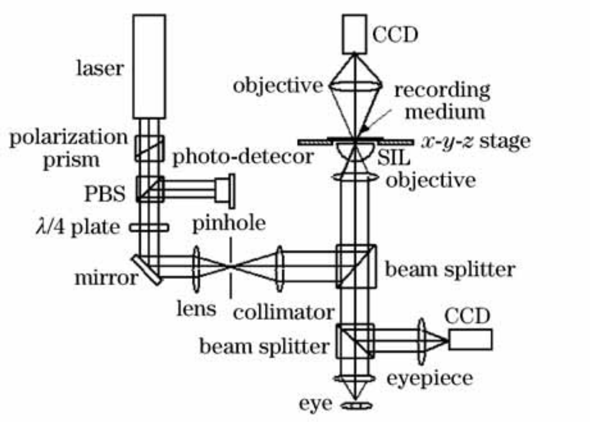

Fig. 1. Schematic diagram of near-field recording system with solid immersion lens.

by the charge-coupled device (CCD) camera and eyes.

The experimental system incorporates an inverted optical microscope (Leica DM IRE2) to make the observation and adjustment more precise and convenient. A long-working-distance microscope objective lens with NA = 0.8 is employed in combination with a hemispherical SIL made of ZF6 glass, $n = 1.755$ and radius 1 mm. We chose a hemispherical SIL instead of the super-spherical SIL because of its more relaxed tolerance on the thickness. The recording medium, photoresist, is placed on a three-dimensional (3D) scanning stage with moving range of $70\times70\times70$ μm^3 and positioning accuracy of sub-nanometer. It will ensure the rigorous separation control in SIL recording system and the precise positioning of the medium. To align the optical axis of the objective lens with the SIL, the method of minimizing the astigmatism induced by misalignment is used in experiments. A NSOM is employed to ensure that the focus point of the laser is at the flat surface of the SIL. The near-field optical distribution of the laser spot on the flat surface of the SIL can be obtained. An accurate alignment of the focus can be achieved by measuring the size of the laser spot on the flat surface of the SIL.

The appropriate recording medium, photoresist, for near-field recording should have some essential properties, nanometric resolution, high sensitivity, high optical contrast and low writing threshold, material homogeneity, high thermal stability, high fatigue resistance and rapid response in thin film. For demonstration and verification, the recording marks should be easy to be observed and measured by an optical microscope, NSOM or atomic force microscope (AFM).

The AFM images of recording marks written on the medium layer using the SIL recording system are shown in Fig. 2. The marks appear feature of relief. According to measurement data, full-width at half-maximum (FWHM) of a cross section of a mark is about 240 nm, and the depth is 60 nm. The theoretical value should be $0.61\lambda/(n_{\rm SIL}{\rm NA}) = 0.61 \times 488/(1.755\times0.8) \approx 210$ nm according to Eq. (1). Considering laser coherence and modification of parameter the constant is usually more than 0.61. The experimental result reveals that it agrees with the theoretical expectation.

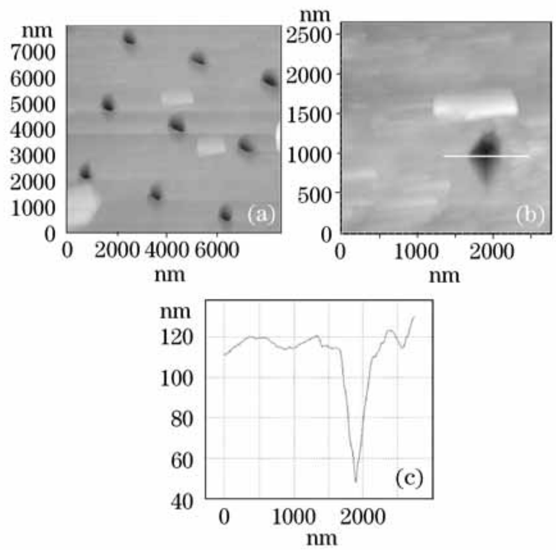

Fig. 2. Recording marks on photoresist by AFM. (a) and (b): Topographic images of recording marks; (c): a cross sectional view of (b) along the white line.

Some factors influencing recording properties have been discussed in our previous paper[9]. These factors include manufacturing and adjusting error of SIL, misalignment of optical system, recording material imperfect, etc..

The manufacturing error of SIL in geometry and surface quality will introduce optical aberration, which will reduce the quality of focusing on the flat surface of the SIL and the near-field coupling based on near-field optics. We have calculated the influence of the manufacturing error. The results show that thickness error of the SIL mainly causes spherical aberration and curvature. The thickness error tolerance for the hemispherical SIL with radius of 1 mm and reflective index of 2.0 is about 20 μm. The thickness error of the SIL in our experiment is less than 5 μm, which ensures that the size of the focused spot will not be increased and the readout signal intensity and contrast will not be influenced.

The misalignment of the optical axis and defocus possibly make focusing spot size outspread and influence recording mark size and density. The calculation results show that the misalignment between the SIL center and the optical axis will mostly cause astigmatism with some curvature and spherical aberration. The deviation within 20 μm in lateral position of a SIL with radius of 1 mm and reflective index of 2.0 has little effect on the size of the focused spot and readout signal. For a perfect hemisphere SIL, the ideal situation is that the light is focused at the center of the SIL's bottom.

The sensitivity of the photoresist in the experiment is not satisfactory so the writing time is at least more than 1 minute with the 7-mW recording power. It means that the writing threshold is still too high to meet the practical applications. The recording power has some influences on the recording spot size. The relation between the recording power and the recorded pit size with the same writing time is shown in Fig. 3 based on the analysis and comparison of theoretical and experimental results. The spot sizes go up monotonously with the recording power increase. When the recording power is 2 times higher, the spot size just increases 25 percents. At the same time we have found that the recording property depends strongly on the preparation of the recording photoresist special for the near-field recording. There are some differences in the grain homogeneous and sensitivity between the different photoresist materials. The appropriate composite, grain

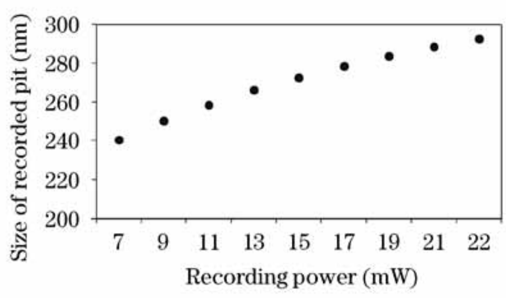

Fig. 3. Relation between the recording power and the size of the recorded pit with the same writing time.

homogeneous, high sensitivity of recording medium should be required to ensure near-field optical writing quality. The ideal recording marks can be obtained with appropriate recording power and writing time.

Although small spot size is obtained using the SlL, and the feasibility to be used to write and read in higher density is revealed, the results shown here are not yet at the limit of the SIL. It is possible to achieve 100-nm spot size and storage densities higher than 50 Gb/in^2 with shorter wavelength and with materials higher index of refraction.

Considering the evanescence coupling mechanism on the SIL bottom surface, it is involved in the principle of near-field optics. The incident light onto the SIL/air interface can be divided into a homogeneous cone for angles smaller than the critical angle θ_c and an inhomogeneous ring for angles larger than θ_c. If the homogeneous cone is blocked by a mask and the inhomogeneous ring propagates into the air, it is possible to obtain higher resolution beyond the diffraction limit with the virtual probe formed by evanescence wave interference[10].

In conclusion, a near-field static recording system based on SIL has been built for demonstrating preliminarily SIL technology in the higher density storage. Appropriate optical adjustments ensure the optical axis of the objective lens coaxial with the SIL and precise separation control ensures the near-field optical coupling condition. The properties of recording medium for near-field recording should be considered carefully. Super-resolution recording marks with 240 nm are obtained, corresponding to a potential storage density of tens gigabits per square inch. It indicates feasibility of SIL technology in the higher density optical storage in the future.

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References

1. F. Zijp, M. B. van der Mark, J. I. Lee, C. A. Verschuren, B. H. W. Hendriks, M. L. M. Balistreri, H. P. Urbach, and M. A. H. van der Aa, in *Technical Digest of Optical Data Storage Topical Meeting* 222 (2004).
2. M. Shinoda, K. Saito, T. Ishimoto, T. Komdo, A. Nakaoki, M. Furuki, M. Takeda, Y. Akiyama, T. Shimouma, and M. Yamamoto, in *Technical Digest of Optical Data Storage Topical Meeting* 225 (2004).
3. T. Milster, Proc. IEEE **88,** 1480 (2000).
4. E. Betzig, J. K. Trautman, R. Wolfe, E. M. Gyorgy, P. L. Finn, M. H. Kryder, and C.-H. Chang, Appl. Phys. Lett. **61,** 142 (1992).
5. S. M. Mansfield and G. S. Kino, Appl. Phys. Lett. **57,** 2615 (1990).
6. S. M. Mansfield, W. R. Studenmund, G. S. Kino, and K. Osato, Opt. Lett. **18,** 305 (1993).
7. B. D. Terris, H. J. Mamin, D. Rugar, W. R. Studenmund, and G. S. Kino, Appl. Phys. Lett. **65,** 388 (1994).
8. Y. H. Lu, P. Wang, J. Y. Zhang, H. Ming, J. P. Xie, and Q. J. Zhang, Chin. J. Lasers (in Chinese) **30,** 145 (2003).
9. Y. Wu, J. Wang, and T. Hong, Proc. SPIE **4930,** 459 (2002).
10. T. Hong, J. Wang, L. Sun, and D. Li, Appl. Phys. Lett. **81,** 3452 (2002).