Directional Beaming by Interaction of Dielectric Nano Surface Structure and Metal: Design for Fabrication of Nanowriter Optical Head

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Abstract — the extraordinary transmission phenomenon has stimulated much interest in recent years. Based on the extraordinary transmission and directional beaming phenomena proposed by Ebbesen *et al.*, a new optical head structures, nonmetal optical head, are presented in this letter. Nonmetal optical head composed of dielectric surface grating on a metallic thin film was proposed. We also offer the physical origin for the directional beaming of light emerging from a single subwavelength slit in the metallic film that has dielectric grating feature on the exit side. Both of experiments and numerical simulations were implemented, and they were shown eventually to agree with this surface plasmon diffraction very well.

The main reason for designing nonmetal optical head proposed in this letter is for mass production possibilities of nanoimprint technique. It is very important to know the mechanism which drives the directional beaming phenomenon for nonmetal optical head. Therefore, a design rule for desired nonmetal optical head is presented.

Another novel optical design proposed is double slits optical head. Light emerging from the two slits cross at the desired focal length, which is decided by the distance between the two slits. Also, two light beam interference to become a subwavelength light beam. Various applications may appear because of the understanding of this nano-optics device, from this design, for example, an optical switch or an optical sensor, optical lithography, optical storage, and optical microscopy, and so on.

I. INTRODUCTION

Based on standard aperture theory, a circular hole with diameter (d) smaller than the incident wavelength (λ) has very low transmission, which is proportional to $(d/\lambda)^4$. It has been shown that the transmission is restricted under the manipulation of near field optics with subwavelength holes. Moreover, a subwavelength spot size is maintained within only several nanometers from the aperture.

The extraordinary transmission phenomenon has been stimulated and experimented in recent years. It has been found when illuminating a metallic film perforated with periodic subwavelength apertures, the transmission is unexpected large in certain wavelength regions. Another astounding phenomenon called "directional beaming" was recently published by Ebbesen *et al.* Based on the extraordinary transmission and directional beaming

phenomena proposed, a new optical head structures, nonmetal optical head, are presented in this letter.

Nonmetal optical head is composed of dielectric surface grating on a metallic thin film. The beaming phenomenon can be explained simply via the surface plasmon diffraction along the interface between dielectric and metal. In order to verify the mechanism, both of experiments and numerical simulations were implemented, and they were shown eventually to agree with this surface plasmon diffraction very well. By analyzing the simulation results based on rigorous coupled wave analysis (RCWA), surface plasma is similarly shown to play an important role in the directional beaming phenomenon and extraordinary transmission simultaneously. And it is found nonmetal optical head works as metal optical head previously reported.

Another novel optical design proposed is double slits optical head. Light emerging from the two slits cross at the desired focal length, which is decided by the distance between the two slits. Also, two light beam interference to become a subwavelength light beam. Therefore, by designing the surface structure of double slits optical head, it is possible to achieve subwavelength focal spot with unprecedented focal length that appears to bypass the Rayleigh criteria.

II. NONMETAL OPTICAL HEAD

In this research, Rigorous Coupled Wave Theory (RCWA) is utilized to estimate the incident angle where the reflective grating possesses the strongest absorption, and Finite Difference Time Domain method (FDTD) proceeds to simulate the results on directional beaming according to the angle calculated out. Experiments are also performed to verify the results of simulation.

In Fig. 1 we choose nonmetal material with permittivity $\epsilon_d = 2.25$ in simulation, corresponding to silicon dioxide in real material due to the consideration of fabrication process. The wavelengths of incident light are 520 and 633 nm. The structure of simulation is composed of the silver film with thickness 300nm, and nonmetal surface grating with grating period 550 nm, and grating depth 100nm. Fig. 2(a) and 2(b) are the results of electromagnetic field distribution computed by FDTD. Fig. 2(c) and 2(d) are the far field distribution

maps corresponding to X coordinate, which are transformed from Fig. 2(a) and 2(b) by Fourier transform. And the results in Fig. 2(d) and 2(e) are obtained by utilizing RCWA to compute the lowest reflectance corresponding to the incident angle of light on reflective gratings.

Fig. 1 Parameters of nonmetal optics head

Fig. 2 Results of results of electromagnetic field distribution of nonmetal optical head with $\epsilon_d = 2.25$

From the simulation results above, no matter how the grating period p , the grating depth t , or the wavelength of incident light λ change for $\epsilon_d = 2.25$, the absorption angle of reflective gratings coincides with the directional beaming angle of optical head.

III. OPTICAL HEAD WITH DOUBLE SLITS

In the view of the discussion above, if the energy of incident light can be absorbed by the surface grating of optical head, when altering the period and depth of the

surface grating, it is possible to adjust the beaming angle of exit light that modulated by the surface grating. While introducing the structure of double slits, we should first confirm whether the electromagnetic wave is modulated by the surface grating, so that varying the period of grating would lead to the different angle of exit light.

The design purpose of double slits has two reasons: First, when two exit light beams intersect, it will cause an interfered light spot with subwavelength scale. What is more important, the distance F from the optical head to the intersection spot of two exit light beams, which is corresponding to the focal length of lens, is determined by the distance of two slits L . As Fig. 3 shows, the angle of exit light beam is dependent on surface grating, and F is proportional to L . In summary, the design purpose of double slits is to solve the difficulties of focusing by lens that when smaller the light spot is, shorter the length of focus is.

Fig. 3 Double slits optical head can utilize distance between slits to determine focal depth

Fig. 4 is the distribution of Poynting vector simulated by FDTD with the thickness of silver film $t = 300\text{nm}$, the thickness and pitch of the surface grating $d = 55\text{nm}$, $p = 550\text{nm}$, and the distance between two slits $L = 4.25\mu\text{m}$, and wavelength of incident light is 520nm . In Fig. 4, the white arrow points out the position where two exit lights intersect, and the distance between surface structure and this intersection with maximum energy distribution of main lobe is $4.32\mu\text{m}$. The FWHM of main lobe is about 348nm . By the way, definition of working distance is the interval between the two ends where the energy decays to 80 percentage of the maximum energy.

Fig. 4 the distribution of Poynting vector with the thickness and pitch of the surface grating $d = 55\text{ nm}$, $p = 550\text{ nm}$, and the distance between two slits $L = 4.25\text{ }\mu\text{m}$, and wavelength of incident light is 520nm .

IV. EXPERIMENT

Fig. 5 is the AFM result of metallic optical head with double slits and surface structure fabricated by FIB. The depth (d) and pitch (p) of the surface grating are 60 nm and 600 nm respectively, and the distances between slits are (A) $L = 7.036 \mu\text{m}$ and (B) $L = 3.519 \mu\text{m}$.

Fig. 5 AFM result of metallic optical head with double slits and surface structure fabricated by FIB.

In experiment, a 520nm bandpass color filter was utilized to observing directional beaming of the two optical heads illuminated normally with halogen source, and recording the images with different cross sections of 0 to 12μm from the surface structure. Surface structure of these two optical heads includes not only double slits but also corrugations inside and outside the space between two slits (as Fig. 6). In Fig. 7, there are four exit lights to be observed. As the section observed getting higher, (A) at 10μm, there are only three beams to be observed and the two central beams overlap each other. The two central lights overlap at 6μm for (B). Therefore, the beaming angles can be calculated to 19.70° and 16.34° respectively in optical heads (A) and (B) by the height F and the interval L between slits. Comparing to the reflective grating with period 600nm and depth 60nm, the minimum reflectance occurs at 20 degrees, and the result of optical head (A) is very close to one of theoretical reflective grating.

Fig. 6 Surface structure of these two optical heads includes not only double slits but also corrugations inside and outside the space between two slits.

	(A)	(B)
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0μm		
2μm		
4μm		
6μm		
8μm		
10μm		
12μm		

Fig. 7 Images with different cross sections observed of 0 to 12μm from the surface structure.

V. CONCLUSION

Our research proposed two novel designs of directional beaming optical head: Nonmetal optical head and double slit optical head. The contributions of the two designs are as follows.

The structure of the nonmetal optical head is dielectric surface grating on the metal thin film. In order to

demonstrate that nonmetal optical head is feasible for directional beaming, we have investigated with simulation and experiment. It is more important to further probe into the reason inducing directional beaming phenomenon of the nonmetal optical head in this research, analyze its physical mechanism, and find that surface plasma plays an important role in the directional beaming phenomenon of the nonmetal optical head. The discussion on the physical mechanism of the nonmetal optical head can be as the basis of directional beaming phenomenon.

The purpose of nonmetal optical head design is to offer the possibility of mass production of directional beaming optical head. We also provide the material choice of designing the optical head under different wavelength, and the determination of exit angle which can be obtained with the minimum reflectance of reflective grating. Therefore, this research possesses a complete procedure of designing the nonmetal optical head.

In our research, another novel design is the double slits optical head. The double slits optical head can get different focal distances by changing the distances of two slits. The two exit interfered lights can obtain subwavelength focused beam at intersection of the two exit beams. Therefore, the double slits optical head can achieve an excellent focused beam that could be reached by very expensive lenses. In brief, our research promotes its application with the novel optical head structure, and investigates a further knowledge of its physical mechanism.

VI. REFERENCES

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