Evanescent Light Enhancement in a Nanometer Aperture Surrounded by Corrugated Metal Thin Film for a Terabyte Optical Disk Head

Kenya Goto, Takahito Ono, and Yong-Joo Kim

***Abstract*—An ultrahigh density optical disk head which utilizes evanescent light (near-field light) had been designed to enhance the near-field optical wave for the throughput increment using the surface plasmon polariton resonance effect between the light inside the near-field optical head and nano-fabricated corrugated metal thin film. The theoretical analysis is discussed with the emphasis on the two- and three-dimensional simulation using finite difference time domain method. It is also experimentally shown that the near-field light enhancement in a waveguide of a clad covered with corrugated gold thin film was observed and that the near-field light enhancement in a waveguide without the film was not. If the corrugation pitch and the focused laser wavelength used with self-aligned microlens are designed properly, more than 20% throughput will be realized using nanometer fabricated metallic grating.**

***Index Terms*—Evanescent wave, nano-aperture, nano-fabrication, near-field optics, surface plasmon, terabyte optical memory.**

I. Introduction

NEAR-FIELD optical systems have been considered as one of the candidates for the optical data storage of the next generation, which will be of ultrahigh density and of ultrahigh data rate [1]. However, an evanescent light power from a nano-size aperture is very weak due to the cutoff wavelength and low optical throughput, resulting in many difficulties to apply it to the real optical data storage. To improve the optical efficiency of nano-aperture probe and realize fast data transfer rate, the parallel optical array head using near-field optics has been proposed and prepared using a vertical cavity surface emitting laser (VCSEL) array and a flat-tip microprobe array [2]. We are trying to make the evanescent light enhancement using surface plasmon polariton (SPP) resonances [3] between the laser light and a newly developed nano-fabricated grating structure on thin gold film over the near-field optical head. In this paper, both theoretical analysis and some experimental results are shown. Large output enhancement of the evanescent light from a 30-nm aperture hole surrounded by corrugated thin gold film is obtained by three-dimensional (3-D) finite difference time domain (FDTD) simulation. For the surface flat type optical head with nano- fabricated corrugation metallic film on the top surface of the head, some simple experiments also show the evanescent wave enhancement effect by not using the plane GaP head and the designed input wavelength but by using a two-dimensional (2-D) SiO_2 waveguide on Si substrate even with the light of not precisely designed wavelength. The experiment also shows the SPP enhancement effect in the grating structure even though there is no perfect resonance condition between the SPP wavelength and the evanescent wavelength inside the head. These predicts that the corrugated nano-fabrication technology enable us the tera byte optical disk and very rapid data transfer rate optical disk system using a 2-D VCSEL array.

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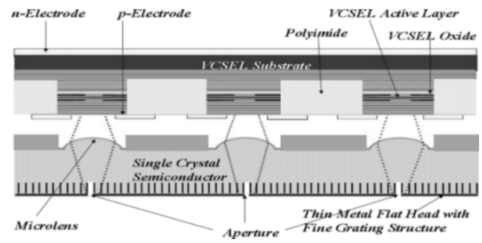

Fig. 1. Cross-sectional view of the new near-field optical head structure, which consists of 2-D VCSEL, micro-lens (10 μm Φ) that is covered with corrugated metallic film, and 30 nm aperture array.

II. Optical Head With New Structure

The new structure of our ultrahigh density and simultaneously ultrahigh data rate head to record the data on and read from super-multi-tracks consists of 2-D VCSEL, 2-D microlens, and 2-D nanofabricated aperture array [2]–[4], [6]–[9]. The realization of smaller laser beam spot with enough power for writing bits on an optical disk is an important requirement for increasing the memory capacity. The integrated structure of VCSEL and flat-tip microprobe arrays for the purpose of utilization of the near-field optics have also been studied, one of which is shown in Fig. 1 for producing more compact and efficient optical array head. The laser beam from each VCSEL is focused through each micro-lens at the each nano-aperture hole. The alignment of the focal point and the nano-aperture position is very sophisticated as shown in the previous report [5]. The SPP wave is generated on the thin gold metallic film by electric field of transverse magnetic (TM) mode of evanescent light from the VCSEL. The inner surface of the gold metallic thin film is fabricated in fine structured corrugation of 10-nm widths, 30-nm depths, and 118-nm pitches, of which each structure is exaggeratedly represented in Fig. 1 and the resonance effects had been reported in previous report [3], [6], which had calculated by 2-D FDTD method. The SPP generated on the surface of the thin metallic film will makes resonance with the grating pitch of the metallic film inside. In order to excite SPP by irradiated light it is required to match the phase velocity between the incident light and the SPP. Equation (1) below shows dispersion component $\kappa_{\rm dx}$ along the metallic surface of incident light, which has an incident angle θ to the corrugated metal surface. $\kappa_{\rm ix}$ and $\rm g_n$ in (1) are the wave number component of the incident light and inverse grid of the grating, respectively

$$\kappa_{dx} = \kappa_{ix} + g_n = \frac{\omega}{c}\sqrt{\varepsilon_m}\sin\theta + \frac{2\pi}{a}n \tag{1}$$

κ_{dx} : input light wave number component along metallic grating surface which irradiated with angle θ

$$\kappa_{sp} = \frac{\omega}{c}\sqrt{\varepsilon_m}\left(\frac{\omega^2 - \omega_p^2}{(\varepsilon_m+1)\omega^2 - \omega_p^2}\right)^{\frac{1}{2}} \tag{2}$$

κ_{ix} : wave number of input laser light

κ_{sp} : wave number of surface plasmon polariton

$\rm g_n$: inverse grating, $\rm a$: pitch $\rm N = 1, 2, 3.$

The symbol ω, C, $\varepsilon_{\rm m}$, a, n means frequency of light, light velocity, permissivity, grid period, and integer number. Equation (2) shows wave number $\kappa_{\rm sp}$ for the dispersion curve of surface plasmon polariton wave, where $\omega_{\rm p}$ is plasma frequency. Fig. 2 shows the dispersion relation of incident light wave and surface plasmon polariton wave. In order to get a solution for satisfying $\kappa_{\rm dx} = \kappa_{\rm sp}$ the metallic grid plays an important role, which makes $\kappa_{\rm dx}$ increase in proportion to $\rm g_n$ of the grid when the phase matching occurs by varying the incident angle θ.

III. Simulation by FDTD Method

Ebbesen *et al.* [6] reported the highly unusual transmission properties of metal film perforated with a periodic array of subwavelength holes [7]. Though light in the visible to infrared range can not relate to the SSP enhancement on the metal-air interface, it is possible to couple the SPP to metal surface if a periodic structure of subwavelength holes is prepared on the metal film as mentioned above. Thus, we tried to add the periodic structural concept on the original integrated VCSEL microprobe array head to enhance the optical throughput, as shown in Fig. 1. A periodic metal grating of subwavelength pitch is introduced on the bottom of semiconductor material with the nanometer size apertures. The revised optical array head also includes VCSEL and microlens arrays so the light from VCSEL will be focused on the nano-apertures which are aligned to the center of microlens as described before. Since the weak evanescent waves excite resonantly the SPP waves with the fine metal corrugation, this kind of head structure is designed, where the resonant pitch of the light waves propagated inside the non-doped GaP material. All parameters were calculated using a 2-D FDTD method. One of the very interesting results was obtained, where resonant enhancement of the evanescent light with the grating pitch can be seen with the grating pitch variation as shown in Fig. 3 [6]. Using 3-D FDTD simulation for the flat type with nano-fabricated corrugation as shown in Fig. 4, large output enhancement of the evanescent light is obtained as shown in Fig. 5, even through we did not use the focal spots of microlens array around the apertures because of lack of computation ability used in this studies. In this simulation, 5-nm cell sizes are used. If it is calculated using the spherical wave combined with microlens, then the enhancement will be bigger than this result.

There had been much difficulty in that the cell size in this simulation is 5-nm cubic, resulting in the total cell number of $8 \cdot 10^9$ for the 10 μm microlens, which is too big to be simulated. Instead of using the microlens, only plane wave had been used for only 2 μm cubic region (5-nm cell number is only 400) with varying the incident light beam angle as 0°, 5°, 10°, and 20° (see Fig. 6).

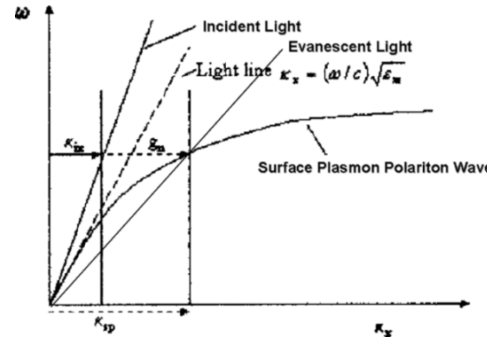

Fig. 2. Dispersion relation of incident light and SPP wave.

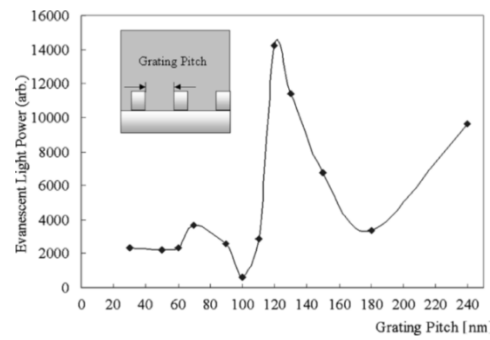

Fig. 3. Evanescent light power (electric field of light wave to the second power) VS nano structure grating pitch in the corrugated metallic film on the top of this head.

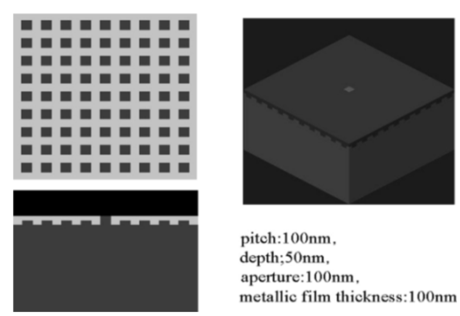

Fig. 4. Schematic figure in the 3-D simulation. In this case only one element of the integrated optical head is three dimensionally shown without VCSEL. A nano-aperture surrounded by fine gold grating structure can be seen. The cell size in 3-D FDTD simulation is 5 nm, then luck of memory capacity prevents us from use of spherical wave. The results followed this figure are used only the plane wave irradiation, i.e., there is no focusing element like lens.

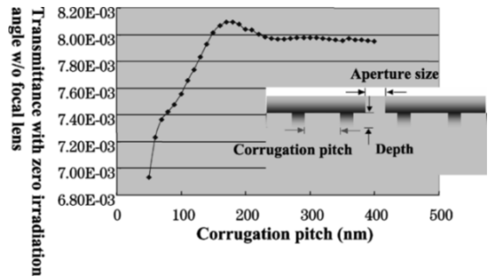

Fig. 5. One of the 3-D simulation results for the evanescent light power increment by the resonance effect of the SPP in the metallic thin film covered to the flat optical head. This is the near-field light power transmittance characteristics for the case of no focal lens used to concentrate the irradiated laser power to the 30-nm aperture filled with air opened in the metallic film with incident light angle of 0°.

If the spherical light wave (focused light beam) is used with the microlens, much more large evanescent light power will be observed in 3-D simulation. From Fig. 2, it can be observed that the throughput efficiency enhancement is occurred by corrugated metallic (gold) thin film owing to the SPP wave resonance and the phase velocity matching by the incident angle variation. It is also seen by calculation that the 30-nm aperture in the thin metallic film (thickness is changed in four cases as 30, 50, and 80 nm) should be filled with the same material as substrate (GaP in the simulation case) used in the head so as to get more higher evanescent light power. The result is shown in Fig. 7 (3-D FDTD simulation).

IV. Experimental Device

The new optical array head includes VCSEL array, microlens array, and nano-apertures on a thin metal film. However, in the experiment more simple device was used without the microlens and using Si substrate to confirm the enhancement effect in the corrugation structure. The reason for selected Si wafer rather than GaP wafer used in the simulation is; Si wafer is very easy to deal with etching and various kinds of processing.

A surface waveguide with light beam of visible wavelength was used in this experiment as shown in Fig. 8. Two-dimensional groove patterning was formed on the Si substrate by utilization of the ultrahigh resolution process and the dry-etching process using the SF_6 reactive ion etching method shown in Fig. 9. In order to increase the optical transmission through the nano-apertures, we prepared such a waveguide structure, because Si absorbs the light in the visible region. Nano-apertures of 100 nm diameter in this experiment are formed on the metal film by focus ion beam (FIB). The narrow grating grooves are prepared successfully of width and pitch with each around 25 and 236 nm, respectively, as shown in Fig. 10. This device is not the exact resonant pitch and not the optimum width, however we were able to observe the light enhancement phenomenon by the corrugated metallic film. Increment of the evanescent light in this experiment was about four times with waveguide structure as shown in the next data.

V. Fabrication Process

It is really important to fabricate the grating width as narrow as possible as shown in the previous report [3], [6], [9], [10],

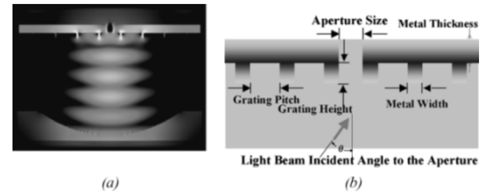

Fig. 6. Cell size of this 3-D FTDT simulation is 5 nm and the lens diameter is 10 μm. The total cell number will be $8 \cdot 10^9$, which is too large to be simulated. Then only plane wave without using the microlens (ML) is used in the 3-D simulation with input angle changing only four points, that are 0°, 5°, 10°, and 20°. (a) Original one with 10 μm lens. (b) Simulated one without ML lens.

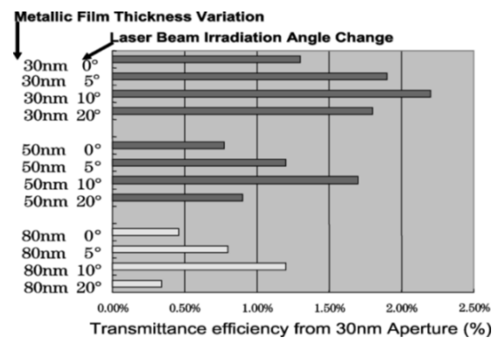

Fig. 7. Evanescent light power transmittance with the corrugated metallic film thickness variation. In each case the incident light angles to the aperture hole are changed. Throughput efficiency was obtained up to 2.2%, even if there is no focal beam microlens used in the GaP optical head.

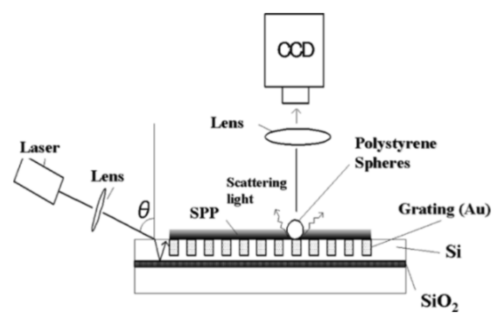

Fig. 8. Experimental apparatus using Si wafer waveguide and visible laser beam as the input light in the waveguide, half of which is formed by the nano-fabricated grating and half of it is no-grating structure.

however, to fabricate it using conventional EB lithography is very difficult. We adopt simpler method to use silicon wafer which is easy to be fabricate wider grids and deposit with 30-nm thickness Cr film, which is etched over the substrate except side film of the grid pattern as shown in Fig. 9(e). After filling the groove with photo resist by spin coating (f), the resist on the surface is etched by FAB and the fine groove shape of the side width is transferred to Si substrate (i). Gold is deposited after getting rid of the resist from the substrate (j) and the surface gold is removed by FAB (k). After process (k), center aperture is formed by FIB. This process has the feature that the Cr film thickness will turn to the grid width. A SEM photo picture after process (h) is shown in Fig. 10, where fine (25 nm width) groove width can be seen after etching Cr film which was the side deposition in the Si substrate.

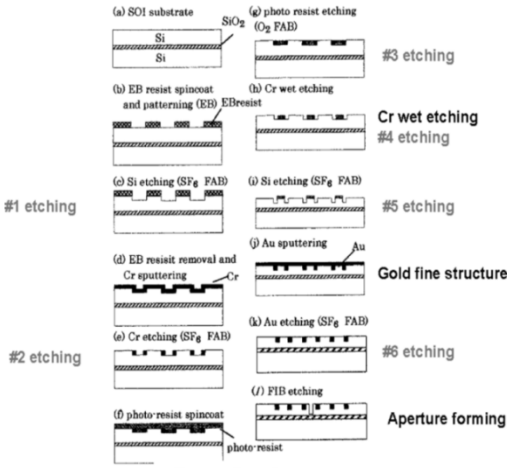

Fig. 9. Nano-fabrication process flow chart for the grid. (a) SOI substrate. (b) EB resist spincoat and patterning (EB). (c) Si etching $(\mathrm{SF_6\ FAB})$. (d) EB resisit removal and Cr sputtering. (e) Cr etching $(\mathrm{SF_6\ FAB})$. (f) photo resist spincoat. (g) Photo resist etching $(\mathrm{O_2\ FAB})$. (h) Cr wet etching. (i) Si etching $(\mathrm{SF_6\ FAB})$. (j) Au sputtering. (k) Au etching $(\mathrm{SF_6\ FAB})$. (l) FIB etching.

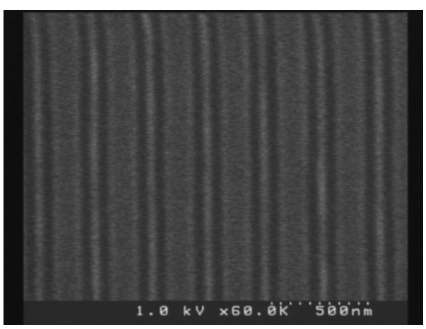

Fig. 10. SEM image after Cr etching at process step (h).

VI. EXPERIMENT

Experiments to ensure the enhancement of the evanescent light by the corrugated gold metallic film, or the gold grid were performed using the apparatus shown in Fig. 8. As this experiment uses no lens focused around the aperture, it is easily imagined that the evanescent light from the aperture is very weak. As telling the difference between the weak light and the scattering light from the gold nano particle residual on the surface is very difficult, two polystyrene spheres of 2.8 $\mu\mathrm{m}\ \Phi$ were placed on both grid and no grid (shown in Fig. 11) and the scattered light from these spheres were observed by CCD camera using 682-nm laser light incidence with incident angle variation. The CCD image when the incident angle is 16° is shown in Fig. 12. Fig. 13 is the profile of $\mathrm{A} - \mathrm{A}'$ cross section in Fig. 12. There is a clear difference from the polystyrene (PS) sphere on the no grid which is very weak compared from the PS on the grid.

VII. DISCUSSION

Fabrication process and theoretical analysis for the new integrated array head are discussed with the emphasis on the FDTD simulation for the metallic grating structure. More than 2.2% evanescent light could be obtained from a 30-nm aperture even

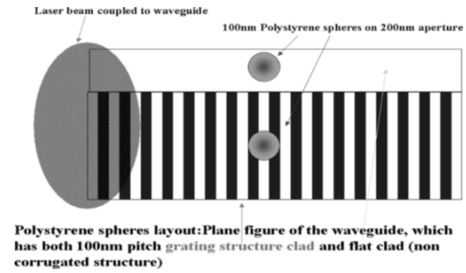

Fig. 11. One of the experimental results for showing scattered light intensity difference between two PS spheres. The PS sphere on the grating waveguide shows stronger scattering light compared to the PS sphere on the plane waveguide without grating.

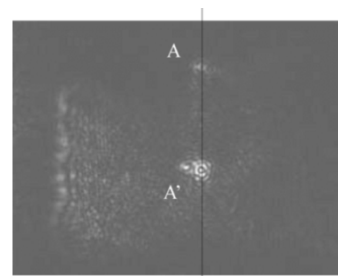

Fig. 12. Scattering light intensity difference between from the corrugated metallic surface and from the noncorrugated one.

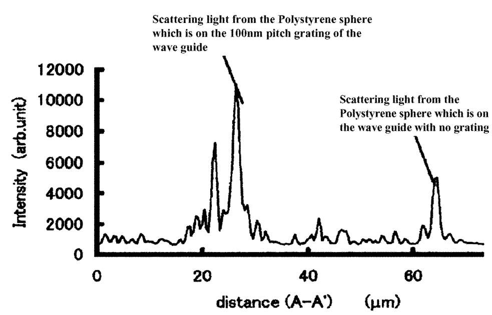

Fig. 13. Brightness of $\mathrm{A} - \mathrm{A}'$ cross section in Fig. 12. There is about four times difference between PS spheres which is on the metallic grating and is not on the metallic grating structure.

if there is no microlens used in Fig. 7. This result shows an enormous increment for the evanescent light through the nano-aperture compared to our conventional experimental data [7]. The experimental result here is not a larger enhancement than the expected one, partly because there is not a precise resonance between the light wavelength and the corrugation pitch in the grating periodicity. In near future, we could make experimental work with much higher throughput efficiency using focusing laser beam, i.e., using spherical wave to each aperture. Also, we could get larger evanescent light output to write bits on the optical disk.

VIII. CONCLUSION

It is good news that we were able to observe evanescent light enhancement by corrugated metal thin film due to the SPP by both 3-D FDTD simulation and a simple experiment. And the incident angle changing experiment data (Fig. 14) are also coincidence with the simulation data of Fig. 7. Next, we are planning to fabricate the similar structure as showed in Fig. 1 for using the

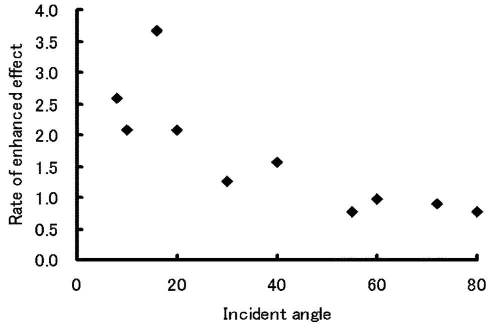

Fig. 14. Experimental data of optimum incident angle of the Fig. 8. About 15° of the incident angle θ in the Fig. 8 is optimum value.

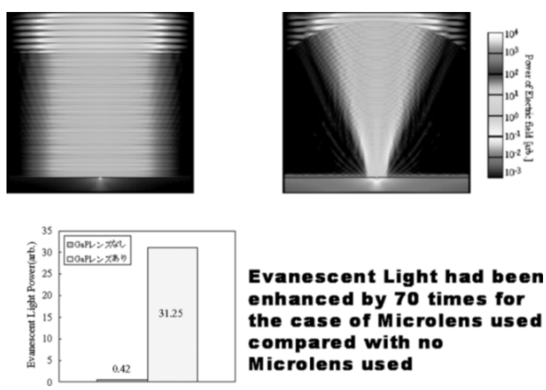

Fig. 15. Microlens makes 70 times light power increment in this near-field optical head (2-D FDTD simulation result).

resonant light wavelength to meet the corrugation pitch. In order to increase the optical power of the evanescent light from the super-parallel 2-D VCSEL array, the head structure consisting of the microlens array and flat face aperture array with 30-nm diameter should be prepared with thin and fine corrugated gold metal as mentioned above. Currently we are attempting to develop new integrated VCSEL array head and evaluate the optical properties for realizing the parallel near-field optical data storage. After the establishment of fine engraved metallic periodic grating with nano-fabrication process, the new head will be completed with the attachment process to the VCSEL array. The evanescent light power enhancement between the incident light and metal grating will be a guideline for the future near-field optical data storage application. The comparison simulation of the microlens used and not used in the SPP excitation gives us expectation of larger improvement in evanescent light power enhancement, one of which is shown in Fig. 15.

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