Highly Efficient Waveguide Using Surface Plasmon Polaritons for Thermally Assisted Magnetic Recording

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A technique of light energy transfer for thermally assisted magnetic recording must be the crucial breakthrough not only to confine an optical near-field spot onto a medium efficiently but also to prevent the temperature from rising in a HDD recording head. A waveguide with a plasmon antenna is investigated using a finite-difference time-domain simulation. For the results, an optical near-field antenna with an apex radius of 12 nm and a protruding structure can confine a light down to 8.5 nm full width at half maximum in intensity, even on a continuous medium. Matching the wavenumber of the incident light to that of a surface plasmon polariton by adjusting the incident angle is a useful technique to transfer energy. The efficiency of light delivery with the plasmon waveguide is 60% greater than the efficiency without the plasmon waveguide.

Key words: thermally assisted magnetic recording, surface plasmon polariton, optical near-field, plasmon waveguide

1. Introduction

Thermally assisted magnetic recording (TAMR), which can overcome the superparamagnetic limit of magnetic recording, has attracted growing attention as a key technique to realize ultra-high recording densities of several terabits per square inch (Tbpsi)^{1,2)}. Light energy transfer from a light source to a very small area on a medium is a highly efficient method of locally heating a recording medium^{3,4)}. Low efficiency heating causes not only increases power consumption but also increases the temperature of the whole recording head.

A plasmon waveguide system connected to an optical near-field antenna is important for achieving highly efficient heating. The plasmon waveguide makes it possible to convert light to a surface plasmon polariton (SPP) and to propagate light up to the plasmon antenna⁵⁻⁷⁾. The plasmon antenna can confine the propagated energy on the medium⁸⁻¹⁰⁾.

In this study, to increase the confinement efficiency of an antenna and the conversion efficiency of a plasmon waveguide, we investigated geometric structures of the plasmon antenna and matching of the wavenumber of propagated light with that of an SPP.

2. Confinement of an optical near-field on a continuous medium

A plasmon antenna structure that had a protrusion at the apex of the antenna on a continuous medium was reported¹⁰⁾. The effect of this antenna protrusion was calculated and analyzed by the finite-difference time-domain (FDTD) method. An FDTD-based simulator (Poynting for Optics, Fujitsu, Ltd.)¹¹⁾ was used to analyze electromagnetic fields and SPPs.

A simulation model of a plasmon antenna for electric field calculation is shown in Fig. 1. The calculation area

is $2,000 \times 2,000 \times 2,000 \text{ nm}^3$. The minimum mesh cell size is $0.5 \times 0.5 \times 0.5 \text{ nm}^3$. The Au plasmon antenna has a triangular shape with a 15-nm protrusion at its apex for confining the light on the medium. The antenna has a longitudinal length of 100 nm and a thickness of 40 nm. The apex radius is 12 nm, and the apex angles in the horizontal and vertical directions are 40° and 30° , respectively. The electric field distribution was calculated with and without a continuous Co film. The Co film is located 5 nm from the apex protrusion. The optical constants of the materials¹²⁾ are listed in Table 1. The light source is located 40 nm from the antenna. The wavelength is 780 nm. The light is a plane wave with linear polarization. The intensity distribution is Gaussian with a maximum intensity of 1 V/m. The diameter of the Gaussian distribution ($1/e^2$) is 1,560 nm. The direction of linear polarization is parallel to the longitudinal axis of the antenna.

The electric field distribution without a medium in the X -direction at a distance of 4 nm below the apex of

Fig. 1 Calculation model of confinement of near-field intensity.

the plasmon antenna, whose apex radius is 12 nm, is shown in Fig. 2. The full width at half maximum (FWHM) of the intensity profile is 10.6 nm. However, the FWHM of the electric field distribution with a continuous Co medium in the X -direction, shown in Fig. 3, is 8.5 nm, which is smaller than the FWHM without a medium. The FWHM with the medium at 13 nm in the Y -direction is also smaller than that without the medium at 15.4 nm. These results show that the continuous medium can function as a counter electrode to confine the optical near-field spot when a plasmon antenna with a protruding structure is used.

3. Highly efficient waveguide with a plasmon antenna

Conventional dielectric waveguides can propagate light easily from the source to near the antenna by using the total reflection caused by the difference in refractive indices of the dielectric materials of a core and a clad. The coupling efficiency between an endpoint of a conventional waveguide and a plasmon antenna is not high, because the propagated light cannot be confined beyond the diffraction limit. In our previous work, the efficiency of a light condensed by a lens was 4.4%. An SPP waveguide for energy transportation has been proposed for achieving high efficiency^{5,6,13}. In our study, the energy transfer between the propagating light and the SPP was investigated from the viewpoint of wavenumber matching.

3.1 Simulation model

A calculation model of a plasmon waveguide with a plasmon antenna is shown in Fig. 4. The calculation area is $5,000 \times 5,000 \times 5,000 \text{ nm}^3$. The minimum mesh size is $1 \times 1 \times 1 \text{ nm}^3$. In order to avoid the influence of light reflected from the calculation boundaries, so called perfectly matched layers (PMLs) method¹⁴ was applied. The conventional waveguide is composed of a Ta_2O_5 core and an Al_2O_3 clad. A Au plasmon waveguide is located in the clad of the conventional dielectric waveguide parallel to the core at a distance D . The plasmon waveguide has a plasmon antenna and wings to confine the light energy to the apex of the antenna⁵. The triangular plasmon antenna with a protruding structure is located at an end of the plasmon waveguide. A continuous Co medium is placed 5 nm from the antenna apex. The optical constants of those materials¹² are listed in Table 1. A light source is located at the edge of the conventional waveguide core. The light is a linearly polarized plane wave with a wavelength of 780 nm. The electric field component of the light is parallel to the incident plane, which is in transverse magnetic (TM) mode.

3.2 Geometric properties

First, we optimize the geometric properties of the plasmon waveguide and the plasmon antenna. The

antenna length L and distance D are changed to obtain higher efficiency. The values of L were 90 and 190 nm, and the values of D were 5 and 10 nm. These combinations of L and D are listed as conditions (a–d) in Table 2. The incident angle of light θ_{in} is fixed at 80° .

Intensity distributions in the X -direction at a distance of 4 nm below the apex of the plasmon antenna are shown in Fig. 5. The intensities for $L = 190 \text{ nm}$ are higher than those for $L = 90 \text{ nm}$ because of the resonance of the Au plasmon antenna^{9,10}. The intensity for $D = 5 \text{ nm}$ is higher than that for $D = 10 \text{ nm}$. This fact means the energy transfer from the Ta_2O_5 core to the metallic waveguide strongly depends on the geometric structure of the waveguide. As a result, the intensity under condition (d) is about 10 times higher than that under condition (a). The FWHM of the intensity curve under condition (d) is only 4.5 nm, which is better than that without a waveguide. The

Table 1 Optical constants at a wavelength of 780 nm in vacuum for calculated materials¹².

Material	Reflective Index (n)	Extinction Coefficient (k)
Al_2O_3	1.76	0
Ta_2O_5	2.17	0
Au	0.174	4.86
Co	2.45	4.72

Fig. 2 Intensity distribution in the X -direction without a medium enhanced by a plasmon antenna with an apex diameter of 12 nm.

Fig. 3 Intensity distribution in the X -direction with a continuous Co medium enhanced by a plasmon antenna with an apex diameter of 12 nm.

intensity distribution observed in the X - Y plane under condition (d) is shown in the inset of Fig. 5. Field enhancement is observed only at the antenna apex on the continuous medium. This fact shows that light propagated in the conventional waveguide can be confined by a plasmon antenna with a protrusion combined with a plasmon waveguide even on a flat continuous medium.

3.3 Wavenumber matching

SPPs can be generated at a coincidence point of both angular frequency ω and wavenumber of the SPP k_{spp} and the incident light k . SPPs can be generated above the coincidence point by controlling the wavenumber of the incident light through variation of the incident angle θ_{in} . The SPP wavenumber k_{spp} at an interface between a dielectric material and a metal with an infinite thickness is given by:

$$k_{\text{spp}} = \frac{\omega}{c} \sqrt{\frac{\epsilon_d \epsilon_m}{\epsilon_d + \epsilon_m}}, \quad (1)$$

where c is the speed of light in vacuum, and ϵ_d and ϵ_m are the relative permittivities of the dielectric material and the metal, respectively. The dispersion relation of the SPP at the interface of the $\text{Al}_2\text{O}_3^{(12)}$ clad and the $\text{Au}^{(12)}$ plate is shown in Fig. 6. The SPP wavenumber k_{spp} is 1.51×10^7 rad/m at $\omega = \omega_{780} = 2.42 \times 10^{15}$ rad/s, which is the angular frequency corresponding to a wavelength of 780 nm in vacuum. The wavenumber k_x , which is a component of k projected in the direction of k_{spp} , in the $\text{Ta}_2\text{O}_5^{(12)}$ core, at several incident angles, is also shown in Fig. 6. The slope of the dispersion line of the light, which is called the light line, is reduced by increasing θ_{in} from 0° to 90° . The light line crosses the intersection point between the dispersion curve of the SPP and ω_{780} with incident angle at $\theta_{\text{in}} \approx 60^\circ$, given that the metal thickness is infinite.

A matching condition between k_{spp} and k_x was investigated by changing the incident angle θ_{in} of the light using the geometrically optimized plasmon waveguide and plasmon antenna. The angle θ_{in} was changed from 55° to 80° because the critical angle of total reflection at the interface between the Ta_2O_5 core ($n = 2.17^{(12)}$) and the Al_2O_3 clad ($n = 1.76^{(12)}$) is 54.2° . The light with θ_{in} less than the critical angle cannot be confined in a conventional waveguide. Intensity profiles as a function of θ_{in} are shown in Fig. 7. The peak intensity increases monotonically with decreasing θ_{in} from 80° to 60° , and increases sharply when θ_{in} decreases further to 55° . This phenomenon shows the importance of wavenumber matching between the k_{spp} and k_x for introducing light into the antenna even in an optimized geometrical structure. The plasmon waveguide system achieves an efficiency of 7.3% for utilized light intensity, which is 60% more efficient than the case when only the antenna is used.

The wavenumber of an SPP at an interface of a

Fig. 4 Calculation model of a plasmon waveguide with a plasmon antenna. (a) Front of view and (b) side view. Antenna length L and distance D between the Ta_2O_5 core and the Au antenna are changed to optimize geometrical properties.

Table 2 Calculated conditions for antenna lengths L and distances D .

Condition	Antenna length L (nm)	Distance D (nm)
(a)	90	10
(b)	90	5
(c)	190	10
(d)	190	5

Fig. 5 Intensity distributions enhanced by a plasmon antenna combined with a plasmon waveguide by changing with antenna length L and distance D .

Fig. 6 Dispersion relations of a surface plasmon polariton at an interface between Al_2O_3 and Au and an incident light in Ta_2O_5 at several incident angles θ_{in} ¹²⁾.

Fig. 7 Intensity distributions enhanced by a geometrically optimized plasmon waveguide and plasmon antenna as a function of incident angle θ_{in} .

metal with a finite thickness shifts from k_{spp} at the interface of an infinitely thick metal depending on the metal thickness¹⁵⁾. In addition, the light passing through the metal can couple with another SPP at an opposite interface between the Au and the Al_2O_3 . These two SPPs can interfere at the apex of the antenna. From this discussion, our results suggest that higher intensities can be obtained by considering the effects of the metal thickness and the interference at the apex. Further investigation will clarify the details of the thickness and interference effects.

4. Conclusion

A plasmon antenna with a protrusion combined with a plasmon waveguide was investigated in order to achieve high light delivery efficiency for thermally assisted magnetic recording. As a result, an optical near-field antenna with an apex radius of 12 nm and a protruding structure can confine a light down to 8.5 nm of FWHM intensity even on a continuous medium.

Matching the wavenumber of the incident light to the wavenumber of an SPP by adjusting the incident angle is a useful technique for transferring energy from a propagating light to the antenna apex via an SPP. The efficiency of light delivery with the plasmon waveguide is 60% greater than the efficiency without the plasmon waveguide.

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