Vol 14 No 1, January 2005
1009-1963/2005/14(01)/0133-04

Chinese Physics

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Simulation and optimization of pyramidal AlGaAs probe with ultra-small spot size and high throughput*

Wang Xiao-Qiu(王晓秋)[a)b)†], Wu Shi-Fa(吴世法)[a)],
Jian Guo-Shu(简国树)[a)], and Pan Shi(潘 石)[a)]

[a)] *Department of Physics, Dalian University of Technology, Dalian* 116024, *China*

[b)] *Department of Physics, Dalian University, Dalian* 116622, *China*

(Received 16 December 2003; revised manuscript received 3 September 2004)

In this paper, the light-emitting spot sizes and throughputs of the four types of probes are studied using the finite-difference time-domain method, and these probes are also compared in performance. Among these probes, a pyramidal AlGaAs tip coated entirely with a thin Ag film can provide the highest throughput and a single near-field spot size. Probe coated with a 3nm Ag film and incident light with a wavelength of 800nm seems to offer the optimum condition for high throughput and ultra-small spot size, which enables the realization of ultra-high density storage.

Keywords: near field optical storage, ultra-small spot size, throughput, pyramidal AlGaAs probe, finite-difference time-domain (FDTD) method

PACC: 4230N, 4280T, 4230H

1. Introduction

Presently, there are two directions of research and development towards prospective breakthrough in technologies for optical memory. One is 3D memory, such as multiple-layer memory and the volumetric holographic memory.[1,2] The other is near-field optical memory of the surface recording type. Near-field optical technologies offer new opportunities for realization of a high-density optical storage system.[3,4] The development of a metallic sharpened optical fibre probe with a sub-wavelength aperture has made it possible to realize high-density optical storage beyond the diffraction limit. The key points to promote recording density depend on the optical properties of near-field probe tip such as near-field light spot size, throughput and the gradients of near-field. Because the throughput ratio decreases rapidly with the aperture diameter decreasing,[5−7] the near-field intensity at the tip apex must be considered. In order to simultaneously meet the two contrary demands of higher throughput and smaller light spot size, the parameters of the near-field probe tip such as material, shape and aperture size must be optimized in design. Recently, Yatsui *et al* have studied a series of probes to improve the spatial resolution,[8−10] and several groups have reported cantilevered near-field optical probes based on micromachining.[11−14] Considering the advantages of the various probes,[10] we have proposed a pyramidal AlGaAs probe with a large taper angle (90°), coated entirely with a film a few nanometres thick (see Fig. 1). This probe was fabricated by self-organized liquid phase expitaxy (LPE).[15] The high refractive index of AlGaAs (n=3.3 at λ=800nm) leads to a short effective wavelength inside the probe, which can result in higher throughput and smaller spot size than those of conventional fibre probes made from silica glass.[16] The large taper angle can suppress the light wave travelling inside the probe at a waveguide cut-off frequency of the fibre, at which frequency the throughput will rapidly decrease. Since the effective wavelength inside the probe is not large, propagation of light inside the probe is possible.[17] With a taper angle of 90°, the propagation of light inside the probe avoids intense far-field escape[18] (see Fig.2) in the uncoated probe, and the well-known Kretschmann configuration

*Project supported by the National Science Foundation of China (Grant No 30270367).

†Correspondence to: Xiaoqiu Wang. E-mail: wangxqdl@sina.com

applies to the excitation of surface plasmons. The surface plasmons propagate along the surface of the metallic coating[19] and converge towards the apex of the tip. The thickness of thin metal film needs to be optimized in order to enhance the transmission efficiency and decrease the extinction simultaneously.

In this paper, we focus on the study of the light-emitting spot sizes and throughputs of the four types of probe, and compare these probes in performance. Then, we present the optimum thickness of Ag film coated on a probe and wavelength of the incident wave.

2. Numerical calculation using FDTD method

The finite-difference time-domain (FDTD) method is currently one of the numerical calculation methods used widely in relation to electromagnetic field. This method was originally developed by Yee in 1966.[20] It has been successfully and extensively applied to scattering of electromagnetic field and its interaction with objects. Nowadays this method is generally used in analysis of the optical field, because its resolution of analysis and degree of usefulness have been greatly improved owing to the development of the perfect-match layer (PML) absorption boundary condition.[21]

The optical modelling of the metal coating requires that one take special care in time-domain analyses such as FDTD. At optical frequencies the permittivity defined in the frequency domain is complex, with its real part being negative. To correctly model the time-domain behaviour of the electron oscillations of a metal, we use a kinetic force equation consistent with the Drude free electron model to model the behaviour of thin metal films. For example, the Maxwell equation for curl H is

$$\nabla \times H = \varepsilon \frac{\partial E}{\partial t} + J, \tag{1}$$

where J is the current density given by

$$J = \rho v. \tag{2}$$

The charge density ρ is taken to be constant and v is the electron velocity. This velocity is updated for each time-increment by using the Lorentz force equation

$$m\frac{\partial v}{\partial t} = -eE - \gamma v, \tag{3}$$

where m and e are the mass and charge of the electron respectively, and γ is the damping coefficient and is determined by the damping frequency of the metal.[22]

3. Simulation models

Owing to the advantages of a pyramidal probe tip,[23] we simulate the following tips. We study and compare the light-emitting spot sizes and throughput of the four types of probes: (a) a bare pyramidal AlGaAs probe, (b) an apertureless pyramidal tip coated with an Ag film 3nm thick, (c) a bare pyramidal probe with an aperture of 60nm×60nm, and (d) a pyramidal probe with an aperture of 60 nm×60 nm coated with a metallic film 30nm thick. Figure 1 depicts the geometry of the problem under consideration. The probe is modelled as a pyramidal AlGaAs probe with a taper angle of 90°. At the input to the tip, we launch a light field (λ=800nm) linearly polarized along the x direction. The computer models for the cases of Figs.1(a), 1(b) and 1(c) each consist of 120×120×100 cells and each cell is of $3\times3\times3\text{nm}^3$. The computer model for the case of Fig.1(d) consists of 150×150×100 cells.

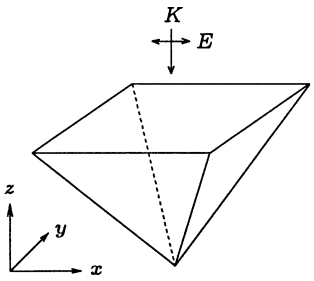


Fig.1. The geometry of the problem under consideration.

4. Simulation results

The near-field distributions of these four configurations are determined by using FDTD method. The throughput is defined as the ratio of total electric field intensity ($|E_x|^2+|E_y|^2+|E_z|^2$) to total incident electric field at the tip apex (z=0nm). Figure 2 is the schematic of light propagation inside the tip. Calculations are shown in Fig.3 and Table 1 respectively. Figure 3 presents the spot sizes of the total electric fields in front of the tip z=0 nm for the cases of Figs.3(a), 3(b), 3(c) and 3(d) respectively. Table 1 shows the numerical results in Fig.3 including two parameters of the full width at half maximum (FWHM) and the throughput of the light-emitting field $|E|^2$ in front of the tip z=0, 12, 24nm respectively. The spot size is defined as the average of the FWHMs of $|E|^2$ along the x and y directions, at z=0nm (i.e. in front of the probe). From Fig.3, we can conclude as follows. A

bare pyramidal AlGaAs probe has a small spot size and low transmission efficiency. That is because a total internal reflection is generated on the tip with the taper angle of 90° (see Fig.2), when the incident wave propagates inside the tip. The light generated by the apex of the tip is essentially evanescent. The throughput of the apertureless pyramidal tip coated with an Ag film 3 nm thick is enhanced by about 2.5 times compared with that of the bare probe (a), and its spot size is almost the same as that of the bare probe (a). In the configuration (b), the surface plasmons excited propagate along the metal layer and converge towards the apex of the tip. For the un-coated aperture pyramidal probe (c), the resulting near-field consists of two maxima in intensity. For the probe with an aperture of 60nm×60nm, coated with a metallic film (d), the near-field consists of two maxima and two inferior maxima in intensity. These results are consistent with those given by Novotny *et al*[24], and Martin and Paulus.[25] The corresponding intensities and spot sizes in front of the probe at z=12 nm and 24nm are shown in Table 1. The throughput ratios for the four types of probes decrease rapidly while the near-field light spot sizes increase. In the probe tip (b), the throughput ratio decreases more rapidly, and the spot size is the smallest.

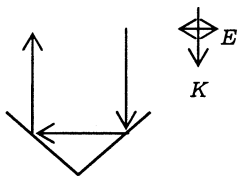


Fig.2. Schematic of light propagation inside the tip.

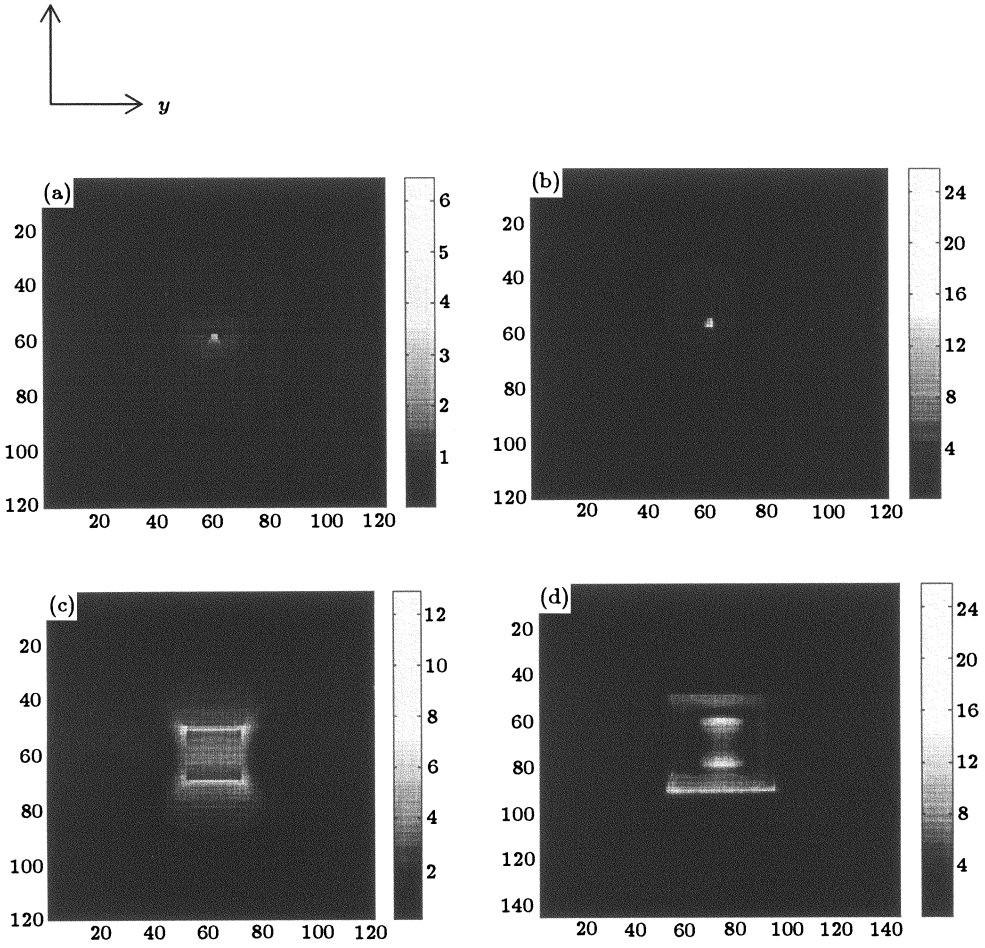


Fig.3. The distributions of the light-emitting spot along xy plane away from the tip of the pyramidal AlGaAs probe at z=0mm. (a) A bare AlGaAs probe (3600nm×3600nm), (b) an apertureless tip coated with an Ag film 3nm thick (3600nm×3600nm), (c) a bare probe with an aperture of 60nm×60nm (3600nm×3600nm), (d) a probe with an aperture of 60nm×60nm coated with an Ag film 30nm thick (4500nm×4500nm).

Table 1. The calculations of FWHM of the light-emitting electric field distributions and the throughput.

	(a)			(b)			(c)			(d)		
Z/nm	0	12	24	0	12	24	0	12	24	0	12	24
field distributions FWHM/ nm	9	58	100	10	60	68	65	85	100	143	185	200
throughput/arb. units	0.20	0.12	0.07	0.50	0.20	0.14	0.25	0.18	0.13	0.70	0.42	0.28

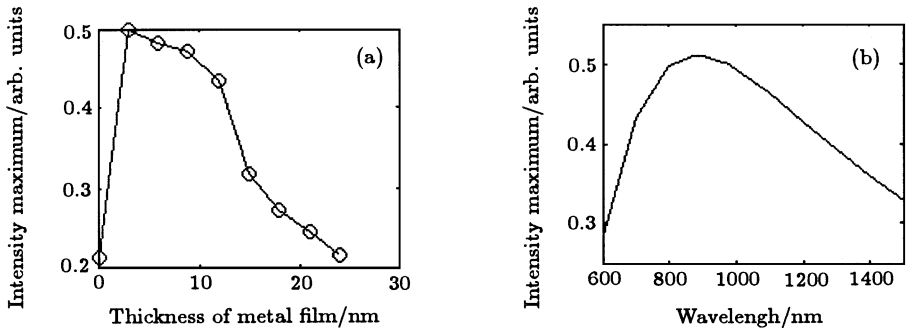


Fig.4. (a) The light intensity as a function of the thickness of the metal film at an incident light wavelength λ=800nm. (b) The light intensity as a function of incident light wavelength, with a metallic film 3nm thick.

In order to optimize the thickness of the coated Ag film and the incident wavelength, the intensity maximum and throughput of an apertureless tip coated with a thin Ag film were investigated as a function of the incident wavelength and the metallic film thickness in front of the tip. Figure 4(a) shows the intensity maximum of the pyramid probe versus the thickness of the metallic film coated. It is seen that the transmission varies with the film thickness in the whole range, and the best thickness is about 3nm. Figure 4(b) shows the intensity maximum of the pyramid probe versus incident light wavelength. The intensity maximum curve shows that the higher value is in the range between wavelengths 800nm and 1000nm, and the maximum transmission is at about λ=880nm.

5. Conclusions

The four types of pyramid probes have been investigated and simulated. Theoretical calculations reveal that a pyramid AlGaAs tip coated entirely with a thin metallic film provides higher throughput and a single near-field spot size that can be smaller than 10nm (FWHM). Spot size and throughput depend on both the thickness of the metallic film coated on the probe and the incident wavelength. The probe coated with an Ag film 3nm thick and the incident light with a wavelength of 800nm seem to offer optimum conditions for high throughput and small spot size, which enables us to realize ultra-high data capacity.

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