Beam manipulating by metallic nano-optic lens containing nonlinear media

Changjun Min, Pei Wang, Xiaojin Jiao, Yan Deng and Hai Ming

Department of Physics, University of Science and Technology of China, Hefei, Anhui, 230026, P.R. China
wangpei@ustc.edu.cn, minghai@ustc.edu.cn

Abstract: Embedding nonlinear media in the slit region of metallic nano-optic lens is proposed as a new method of active modulating the output beam. Two important phenomena, beam deflection and focusing, have been studied in detail. A developed Finite Difference Time Domain (FDTD) method has been performed to account for the nonlinear response. The simulated results show that the deflection angle and focus length can be controlled easily by the intensity of incident light in the structures. The physical principle of the phenomena is explained by the Surface Plasmons (SPs) excitation and Fabry-Pérot (F-P) resonance in the nanoslit.

OCIS codes: (240.6680) Surface Plasmons; (220.2560) Focus; (190.0190) Nonlinear optics

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#82368 - $15.00 USD Received 24 Apr 2007; revised 8 Jul 2007; accepted 11 Jul 2007; published 17 Jul 2007

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1. Introduction

Since Ebbesen first reported the extraordinary optical transmission through a two-dimensional hole array perforated on a metallic film in 1998[1], there has been an explosion of interest in subwavelength metallic structures [2-7]. Surface plasmons (SPs), excited in metallic surface, have been promoted as the primary vector responsible for these phenomena [1-7]. And Fabry-Pérot (F-P) resonance of SPs plays an important role to the enhanced transmission and localized electric-field in the slit on metallic film [7, 8]. These researches open up a new avenue for new types of nano-optic device with variant structures in metallic films [9]. As an application example, new metallic nano-optic lenses have been designed with slits perforated on thin metallic film, which can implement beam deflection and focusing with variant slit depths[10] or slit widths[11]. However, a great challenge that faces SPs research in the coming years is achieving active control of plasmonic signals in nano-optic devices [12]. So recently, nonlinear optical devices based on subwavelength metallic structures have been proposed to actively control plasmonic signals by nonlinear media [13-15]. Compared with usual all-optical devices based on various types of optical nonlinearities, these new nonlinear optical devices have advantages of minisize and stronger nonlinear effects enhanced by SPs confinement and enhancement in metallic structures.

In this paper, we investigate a new type of metallic nano-optic lens consisting of slits with variant widths, filled with Kerr nonlinear media. Each slit is designed to transmit light with specific phase retardation controlled by the intensity of incident light, owing to the nonlinear response. Compared with conventional metallic nano-optic lens, this new lens can actively control the deflection angle and the focus length of output beam, which has great potential practical applications. It is worth to note that the whole element is formed on a planar thin film that is convenient for miniaturization and integration.

2. Principle and simulation method

Considering two closely placed parallel metallic plates, the SPs of each surface will couple and propagate in the form of a waveguide mode for TM-polarized case. The complex propagation constant β can be calculated from the equation [11]

$$\tanh(\sqrt{\beta^2 - k_0^2\varepsilon_d}\,w/2) = -\frac{\varepsilon_d\sqrt{\beta^2 - k_0^2\varepsilon_m}}{\varepsilon_m\sqrt{\beta^2 - k_0^2\varepsilon_d}}, \tag{1}$$

where k_0 is the wave vector of light in free space, ε_m and ε_d are the relative dielectric constants for the metal and the materials in the slit respectively, and w is the slit width. Considering the phase retardation of SPs transmitted through slit with finite length of d, both physical analysis and numerical simulation before show that the product βd plays a dominating role [11]. The imaginary part of β represents the decibel loss coefficient per unit length, which is usually ignorable for light propagation in short slit. We mainly focus on the Re(β/k_0), representing the effective refractive index in the slit and determining the phase retardation.

Figure 1 plots the effective refractive index Re(β/k_0) versus dielectric constant ε_d at different slit widths: w=60,70 and 90 nm. The used metal here is Ag with ε_m= -33.22+ i1.17 at the wavelength of 850nm. It is clear that Re(β/k_0) grows steadily with increasing dielectric constant ε_d , but reduces when the slit width w increases. Obviously, the dispersion relation in Fig.1 implies a potential way of phase modulation by varying the dielectric constant ε_d, which can be implemented with Kerr nonlinear media. It is well known that dielectric constant ε_d in Kerr nonlinear media depends on the intensity of the electric field $|E|^2$:

#82368 - $15.00 USD Received 24 Apr 2007; revised 8 Jul 2007; accepted 11 Jul 2007; published 17 Jul 2007

$$\varepsilon_d = \varepsilon_l + \chi^{(3)} |E|^2, \tag{2}$$

where ε_l is the linear dielectric constant, $\chi^{(3)}$ is the third-order nonlinear susceptibility. In what follows, the linear dielectric constant is chosen to be ε_l =2.25; the third-order nonlinear susceptibility is chosen as a typical value of nonlinear optical materials such as InGaAsP, that is $\chi^{(3)}=1\times10^{-18}m^2/V^2$ [18]. The intensity $|E|^2$ in slits is determined by the intensity of incident light and different in each slit for variant widths. Hence we can manipulate the phase retardation as well as output beam by varying the intensity of incident light.

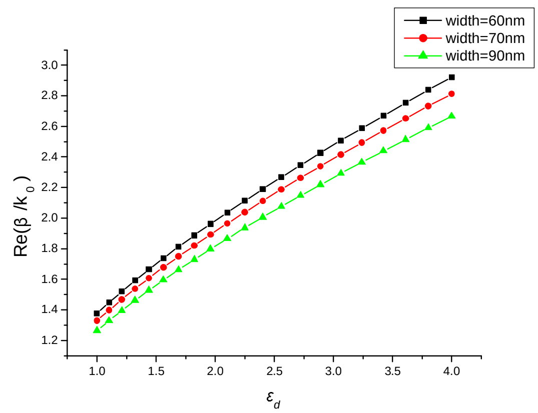

Fig. 1. The effective refractive index as a function of dielectric constant ε_d of the materials in the slit at different slit widths: w=60, 70 and 90 nm.

A developed two-dimensional finite difference time domain (FDTD) method [16] has been performed in our work. The second-order Lorentz dispersion model [17] is used to simulate the metallic film, which has the frequency dependence of the permittivity. In order to account for the nonlinear response of the material inside slits, we import the nonlinear polarization vector $P_{nl}=\varepsilon_0\chi^{(3)}E^3$ [18] into the Maxwell equation of our FDTD program:

$$\nabla \times H = \varepsilon_\infty \frac{\partial E}{\partial t} + \frac{\partial P_l}{\partial t} + \frac{\partial P_{nl}}{\partial t}, \tag{3}$$

where ε_∞ is the relative permittivity at infinite frequency in the Lorentz model, P_l is the linear polarization vector generated by the Lorentz model. The perfectly matched layer (PML) [16] has been used in boundaries of the simulation area.

3. Simulation result and discussion

First of all, we investigate the deflection phenomenon of the beam through a three-slit structure, shown in Fig. 2(a). The structure is formed in a 560-nm-thick silver film with equal slit interspacing of 400 nm (center to center) and slit widths of 90, 70, and 60 nm in sequence from up to down. All the slits are filled with Kerr nonlinear media and illuminated by a TM-polarized plane wave of 850 nm wavelength. The FDTD simulations of electric-field intensity $|E|^2$ distribution at different incident intensities are shown in Fig. 2(b) and Fig. 2(c). In Fig. 2(b), the electric-field amplitude of incident light is chosen as $E_0=1\times10^8$V/m, and the deflection angle (denoted as θ in Fig. 2(a)) of the output beam is small (~8°), which is mainly determined by the phase retardation for variant slit widths. However, the deflection angle θ becomes larger (~24°) as the electric-field amplitude increases to $E_0=2.5\times10^8$V/m in Fig. 2(c), caused by the nonlinear response.

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The reason of the deflection phenomenon can be explained by the Fabry-Pérot resonance of SPs in the nanoslit region. When the incident light illuminates the three-slit structure vertically, the average electric-field intensity $|E|^2$ of the slit at F-P resonance is stronger than the slit out of F-P resonance; hence the effective refractive index increases greatly in the slit at F-P resonance according to Eq. (2). As an example in Fig. 2(c), when E_0 grows from 1×10^8V/m to 2.5×10^8V/m, only the slit with w=60nm achieves F-P resonance, other two slits are out of F-P resonance for different original effective refractive indexes at low intensity (See Fig. 1). So the increased effective refractive index in the slit with w=60nm is larger than the other, which makes the deflection phenomenon more obvious. The active control of deflection angle has great applications to near-field scanning, SPs antenna, etc.

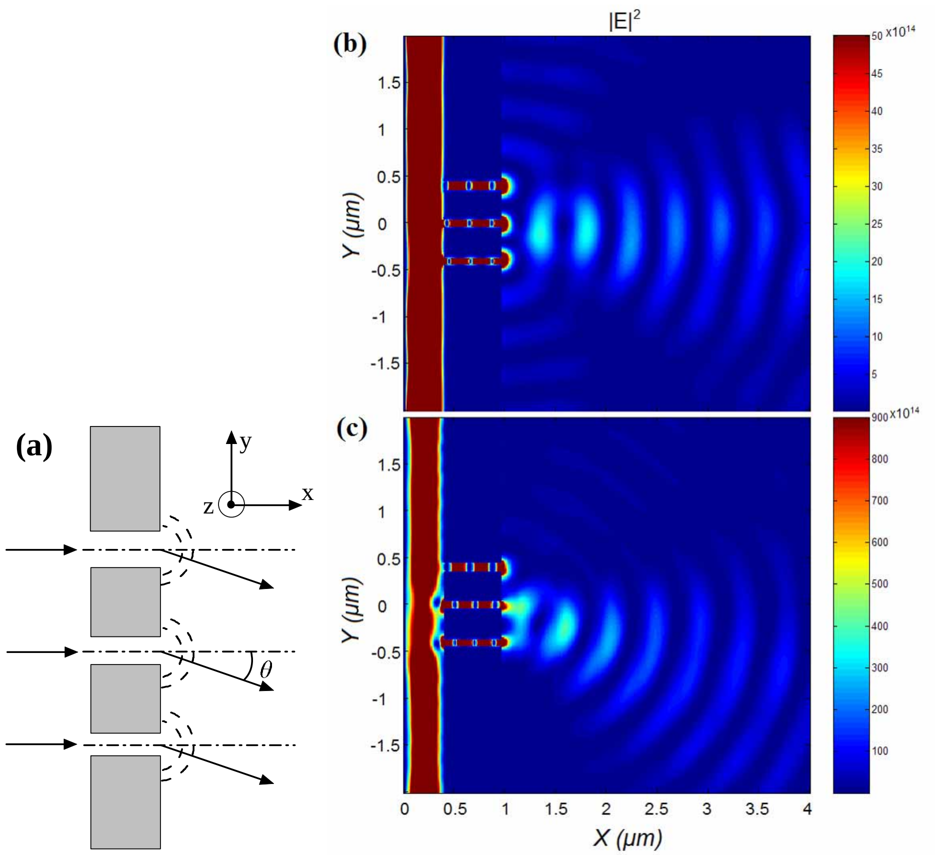

Fig. 2. (a) Schematic view of the three-slit structure under study. The parameters are as follows: the thickness of the Ag film is 560nm, the distance between two silts is 400nm(center to center), the slit width is 90, 70, and 60 nm in sequence from up to down, the deflection angle of the output beam is denoted as θ. A TM-polarized plane wave (850 nm wavelength) is incident from the left side of the slit array. The FDTD simulations of electric-field intensity $|E|^2$ distribution are shown at different incident amplitudes: (b) $E_0=1\times10^8$V/m and (c) $E_0=2.5\times10^8$V/m.

Figure 3 shows FDTD simulation of time-average electric-field intensity $|E|^2$ distribution of beam focusing in a five-slit structure. The positions of focuses are indicated by vertical white lines in x-axis. The thickness of silver film is 570nm and the slit widths in the five-slit array are 100, 70, 60, 70 and 100 nm from up to down. The electric-field amplitudes of the incident light are respective $E_0=1\times10^8$V/m in Fig. 3(a), $E_0=2\times10^8$V/m in Fig. 3(b) and $E_0=3.5\times10^8$V/m in Fig. 3(c). Other parameters are the same with Fig. 2. In Fig. 3(a), a clear focus appears at about 2.7μm away from the exit surface; however, it drops to about 0.6μm with the increased intensity of incident light in Fig. 3(b). The reason of the focus moving is same to the deflection effect above. When the incident amplitude E_0 grows from 1×10^8V/m to 2×10^8V/m, only the centric slit with w=60nm achieves F-P resonance, hence its increased effective refractive index is larger than the slits far from the center, which makes the focus closer to the exit surface, as shown in Fig. 3(b).

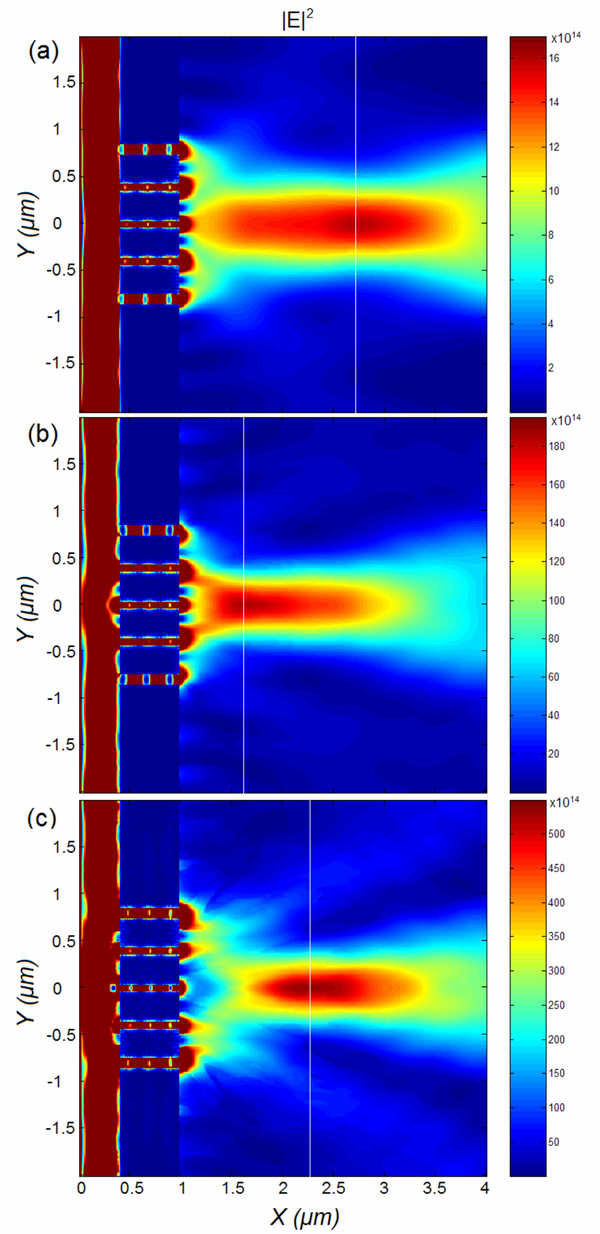

Fig. 3. The FDTD simulation of electric-field intensity $|E|^2$ time-average distribution of beam focusing with a five-slit metallic lens. The parameters are as follows: the thickness of the Ag film is 570nm, the distance between two silts is 400nm(center to center), the slit width is 100, 70, 60, 70 and 100 nm from up to down. A TM-polarized plane wave (850 nm wavelength) is incident from the left side of the slit array. The electric-field amplitude of the incident light is

#82368 - $15.00 USD Received 24 Apr 2007; revised 8 Jul 2007; accepted 11 Jul 2007; published 17 Jul 2007

E_0=1×10^{8}V/m in (a) , E_0=2×10^{8}V/m in (b) and E_0=3.5×10^{8}V/m in (c). The vertical white lines indicate the positions of focuses in *x*-axis.

According to the analysis above, if the incident amplitude E_0 continues increasing, the centric slit may be out of F-P resonance and make the focus far away from the exit surface again, which has been checked in Fig. 3(c). When E_0 grows to 3.5×10^{8}V/m in Fig. 3(c), the slits far from the center achieve F-P resonance instead of the centric slit, hence it is obvious that the focus moves far away from the exit surface, just as expected. In fact, the focus moving is a quasi periodic action owing to the F-P resonance of SPs in nanoslit. Controlling focus by incident light is also very useful in its potential practical application.

4. Conclusion

In this paper, embedding nonlinear media in the slit region of metallic nano-optic lens is proposed as a new method of active modulating the output beam. The work principle of nonlinear media in slit of metallic film is discussed in detail. Two main phenomena, beam deflection and focusing in this metallic nano-optic lens, have been simulated using a developed FDTD method. The simulated results clearly show that the deflection angle and the focus position can be controlled easily by the intensity of incident light. Through analyzing the properties of the beam deflection and focusing, we explain the effects by the theory of Fabry-Pérot resonance of SPs in the nanoslit. We believe that when nonlinear media is embedded within metallic nano-structures, various new phenomena (such as four-wave mixing, bistability effect, etc) will be discovered and more actively-controlled nano-optic devices will be designed.

Acknowledgments

This work is supported by the National Natural Science Foundation of China under Grant No.10474093 and the National Basic Research Program of China under Grant No.2006CB302905.

#82368 - $15.00 USD Received 24 Apr 2007; revised 8 Jul 2007; accepted 11 Jul 2007; published 17 Jul 2007