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Beam focusing by metallic nano-slit array containing nonlinear material

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ABSTRACT A two-dimensional nonlinear finite difference time domain (NFDTD) method is performed to investigate the beam focusing phenomenon in metallic nano-slit array containing nonlinear material. Illuminated by an incident TM-polarized Gauss beam, the arrayed nano-slits transport electro-magnetic energy in the form of surface plasmons (SPs) and provide desired phase retardations for beam focusing, owing to the nonlinear response. The position of focus can be actively controlled by parameters of incident beam, such as the intensity and the beam waist. The physical origin of the focusing effect is discussed by considering SPs mode and nonlinear optical theory.

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1 Introduction

Since Ebbesen et al. [1] first reported the extraordinary optical transmission through a two-dimensional metallic hole array, much interest in Surface Plasmons (SPs) has been excited in subwavelength metallic structures, which opens up a new avenue for designing new types of nano-optic devices [2–6]. In the coming years, a great challenge of SPs research is achieving active control of plasmonic signals in nano-optic devices [7]. Recently, nonlinear optical devices based on subwavelength metallic structures have been proposed to actively control plasmonic signals by nonlinear material [8–11]. Compared with the usual all-optical devices based on various types of optical nonlinearities, these new nonlinear optical devices have the advantage of smaller size and stronger nonlinear effects because of electromagnetic field confinement and enhancement in metallic structures.

In this paper, we investigate an actively controlled structure consisting of nano-slit array in a metallic film, filled with Kerr nonlinear material. Each nano-slit is designed to transmit light with specific phase retardation controlled by nonlinear response. When an incident TM-polarized Gauss beam illuminates the nano-slit array, the phase retardation in each slit is different; hence, the output beam can be shaped and a focusing phenomenon can be observed. It is worth noting that the position of focus is actively manipulated by the incident light, which has potential applications to optical signal processing, etc.

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2 Simulation model and method

Figure 1 shows the schematic figure of the metallic nano-slit array under study. The structure is formed in a 1-μm-thick Ag film with equal slit interspacing $d = 600$ nm (center to center) and slit width $w = 80$ nm. Here we only consider five slits for simplicity of calculation. All slits are filled with Kerr nonlinear material, which includes the parameters: linear dielectric constant $\varepsilon_l = 2.25$ and third-order nonlinear susceptibility $\chi^{(3)} = 1.4 \times 10^{-10}$ esu [12], which is chosen as a typical value of nonlinear optical materials such as InGaAsP. In our simulation, an incident TM-polarized Gauss beam illuminates the metallic film vertically with wavelength $\lambda = 850$ nm, where the dielectric constant of Ag is $\varepsilon_m = -33.22 + i1.17$.

A two-dimensional nonlinear finite difference time domain (NFDTD) method has been used in our work [13]. In order to calculate the nonlinear response of the material within nano-slits, we import the nonlinear polarization vector $P_{nl} = \varepsilon_0 \chi^{(3)} E^3$ [12] into the FDTD program. The second-order Lorentz dispersion model [14] is used to simulate the metallic film. The perfectly matched layer (PML) [13] has been applied to boundaries of the simulated area.

3 Principle and simulation result

Above all, we discuss the physical origin of the beam focusing in our structure. Considering two closely placed parallel metallic plates, the SPs of each surface will be coupled and propagate in the form of a waveguide mode for TM-polarized case. The complex propagation constant β can be calculated from the equation [5]

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

where k_0 is the wave vector of light in free space, ε_m and ε_d are the relative dielectric constant 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

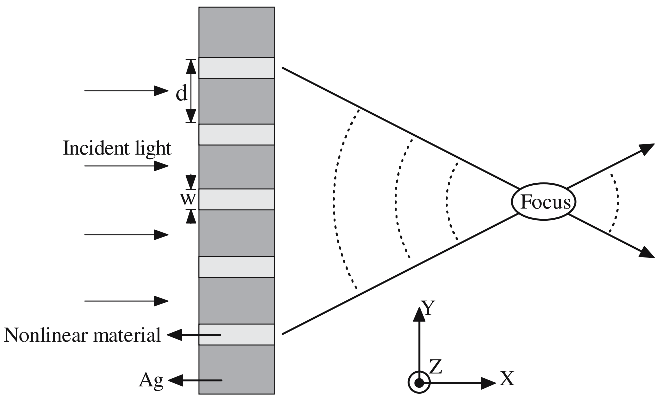

FIGURE 1 A scheme of nano-slit array in metallic film. All the slits are filled with Kerr nonlinear material. A TM-polarized Gauss beam is incident to the slit array from the left side

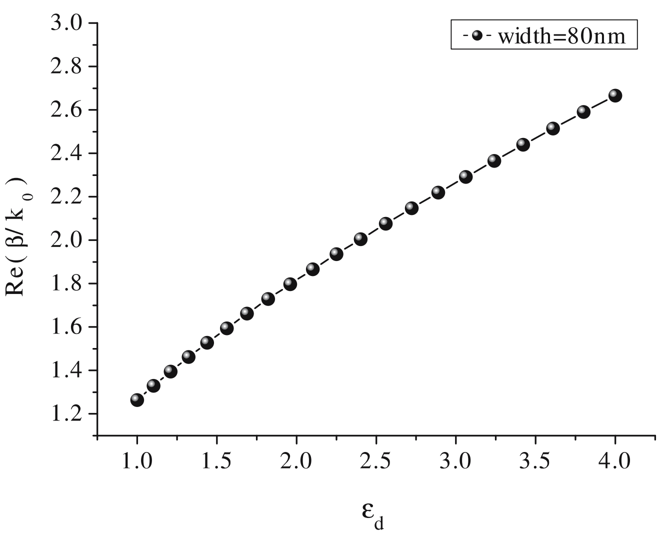

FIGURE 2 The effective refractive index Re (β/k_0) as a function of dielectric constant ε_d of the materials in the slit with the slit width $w = 80$ nm. The used metal is Ag and the wavelength is 850 nm

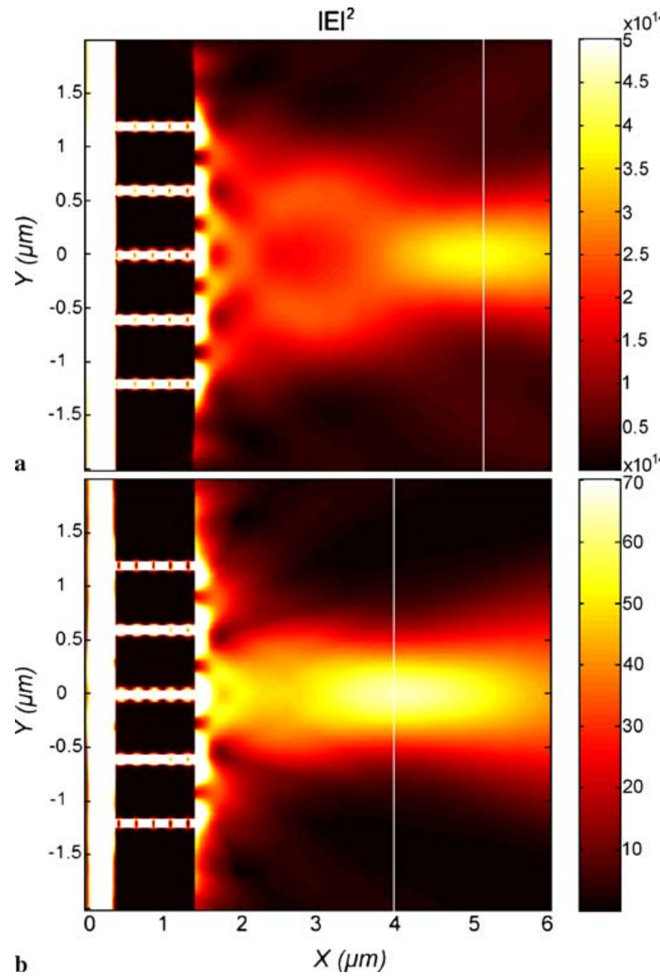

FIGURE 3 The FDTD simulation of the time-average electric-field intensity $|E|^2$ distribution of beam focusing in the five-slit structure. A TM-polarized Gauss beam (850 nm wavelength) is incident from the left side with the beam waist $w_a = 3.2$ µm . The intensity of the incident light is chosen as $I_0 = 1.33$ GW/cm^2 in (**a**) and $I_0 = 5.31$ GW/cm^2 in (**b**). The *white lights* in the figure locate the positions of focuses in x-axis

with finite length of L, both physical analysis and numerical simulation show that the product βL plays the dominating role [5]. The imaginary part of β represents the decibel loss coefficient per unit length, which is small and usually ignorable. So we mainly focus on Re (β/k_0), which represents the effective refractive index inside slit and determines the phase retardation.

Figure 2 plots the effective refractive index Re (β/k_0) as a function of ε_d with slit width $w = 80$ nm. It can be seen clearly that Re (β/k_0) grows steadily with increasing dielectric constant ε_d. The dispersion relation in Fig. 2 implies a way of phase modulation by changing the dielectric constant ε_d, which can be implemented by embedding Kerr nonlinear material into slit. It is well known that the dielectric constant in Kerr nonlinear material depends on the intensity of the electric field $|E|^2$:

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

where ε_l is the linear dielectric constant, $\chi^{(3)}$ is the third-order nonlinear susceptibility. The intensity $|E|^2$ inside slit is determined by the intensity of incident light, which is different in each slit for a Gauss beam. Illuminated by a Gauss beam, the central slit gets stronger intensity $|E|^2$ and more phase retardation than the marginal slits; hence, a focusing phenomenon of output beam will be observed.

In order to check the focusing principle above, we utilize the FDTD method to simulate the beam focusing phenomenon. Influences of the incident beam parameters, including the intensity and the beam waist, are mainly considered. Figure 3 shows the time-average electric-field intensity $|E|^2$ distribution of the five-slit structure with different incident intensities. The intensity of the incident light is chosen as $I_0 = 1.33$ GW/cm^2 in Fig. 3a and $I_0 = 5.31$ GW/cm^2 in Fig. 3b, respectively. In Fig. 3a, a clear focus appears at about 3.8 µm away from the exit surface, just well proving the focusing principle above. However, the focus length drops to about 2.6 µm in Fig. 3b, owing to the increased intensity of incident light. When the intensity of the incident Gauss beam grows from 1.33 GW/cm^2 to 5.31 GW/cm^2, the difference of the incident intensity becomes larger between central slit and marginal slits. According to (2), the difference of the effective

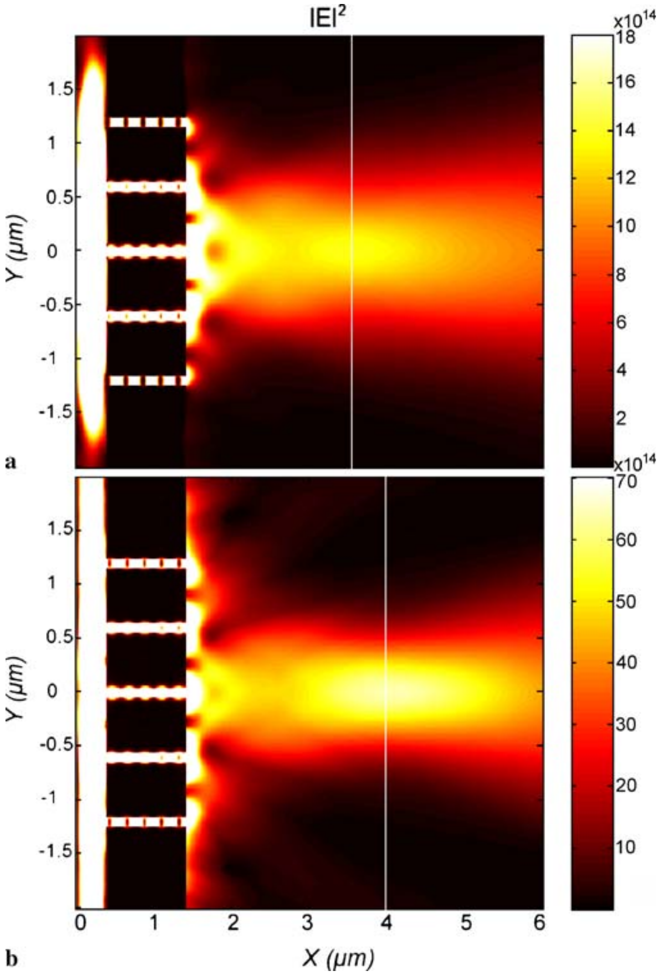

FIGURE 4 The FDTD simulation of the time-average electric-field intensity $|E|^2$ distribution of beam focusing in the five-slit structure. A TM-polarized Gauss beam (850 nm wavelength) is incident from the left side with the intensity $I_0 = 5.31\ \mathrm{GW/cm^2}$. The beam waist of the incident light is chosen as $w_a = 1.6\ \mu\mathrm{m}$ in (**a**) and $w_a = 3.2\ \mu\mathrm{m}$ in (**b**). The *white lights* in the figure locate the positions of focuses in x-axis

refractive index in slits also increases; hence, the focus moves closer to the exit surface, as shown in Fig. 3b.

Figure 4 shows the time-average $|E|^2$ distribution of the five-slit structure with different beam waists. The beam waist of the incident Gauss beam is chosen as $w_a = 1.6\ \mu\mathrm{m}$ in Fig. 4a and $w_a = 3.2\ \mu\mathrm{m}$ in Fig. 4b. It is obvious in Fig. 4 that the focus moves far away from the exit surface when the beam waist increases. It also can be explained by the variance of the effective refractive index in slits. When the beam waist increases, the incident Gauss beam becomes broader, so the difference of the incident intensity decreases between central slit and marginal slits. According to (2), the difference of the effective refractive index in slits decreases, too. Thus the focus moves far away from the exit surface, as shown in Fig. 4b. The active control of focus position by incident light has great potential applications in near-field scanning and detecting.

4 Conclusion

In this paper, embedding nonlinear material in metallic nano-slit array is proposed to actively control the output beam. The principle of beam focusing through the nano-slit array is discussed by SPs mode and nonlinear optical theory. A developed FDTD method has been used to simulate the focusing phenomena and to study the influence of incident beam parameters. As a result, simulated figures clearly show that the focus position can be simply controlled by the intensity or beam waists of incident light. These advantages promise various potential applications in nano-scale beam shaping, nearfield imaging, integrated optics, etc. We believe that when nonlinear material is embedded within metallic nano-structures, more and more new phenomena (such as four-wave mixing, bistability effect, etc.) will be discovered and taken into applications. It is expected that our works are helpful for designing new types of actively-controlled nano-optic devices, and contribute to more applications.

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