

Modulation of Splitting Beam Angle with Metal–Nonlinear Optical Material–Metal (M–NL–M) Array Structure *

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We demonstrate active manipulating plasmonic signals with metal–nonlinear optical material–metal (M–NL–M) arrays consisting of slits with variant widths. The parameters of the M–NL–M array structure are derived by theoretical analysis of dispersion relationship. The splitting angle can be modulated by the incident light intensity, and verified by a nonlinear two-dimensional finite difference time domain method. The physical principle of this phenomenon is analysed from the phase of surface plasmon polaritons and Fabry–Pérot (F–P) resonance in slits.

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The unique properties of surface plasmon polaritons (SPPs) have triggered an explosion of interest in subwavelength structure to manipulate SPP signals, they leads to a new branch of photonics called plasmonics,^[1–2] which is considered to be a very promising area for designing new types of metallic nano-optic devices and for miniaturization of photonic circuits.^[2–3] In the coming years, a great challenge that faces SPP research is achieving active control of plasmonic signals in nano-optic devices.^[1] Recently, nonlinear optical devices based on subwavelength metallic structures have been proposed to actively control plasmonic signals by nonlinear materials.^[4–7]

In this Letter, first we investigate a simple structure with a thin nonlinear optical material film sandwiched by two layers of a metal–nonlinear optical material–metal (M–NL–M) film. Then according to this, we propose an M–NL–M array structure consisting of slits with variant widths. Each nanoslit element 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 arrays,^[8] this new M–NL–M array structure can actively control the splitting angle, which has great potential applications.

As we know, in dielectric waveguide enclosed by metal (MDM), when the width of slit is much smaller than wavelength of incident light, there is only the lowest SPP mode (TM₀) existing in the MDM structure. The dispersion relation equation of SPP(0) mode can be derived from waveguide theory,^[9]

$$\tanh\left(\frac{w\sqrt{\beta^2 - k_0^2\epsilon_d}}{2}\right) = -\frac{\epsilon_d\sqrt{\beta^2 - k_0^2\epsilon_m}}{\epsilon_m\sqrt{\beta^2 - k_0^2\epsilon_d}} \quad (1)$$

where k_0 is the wave vector of light in vacuum, ϵ_d

and ϵ_m are the permittivities for the metal and dielectric medium, w is the slit width, β is the propagation constant of SPPs along the slit to determine the phase of SPP(0) in the slit. Equation (1) shows that β depends on w and ϵ_d if the metal is chosen and the incident light wavelength are fixed. Figure 2 plots the effective refractive index $\text{Re}(\beta/k_0)$ versus the dielectric constant ϵ_d at different slit widths: $w = 50, 60, 70, 80$ and 110 nm. The metal used here is Ag with $\epsilon_m = -32.217 + i1.726$ at the wavelength of 850 nm. It is clear to see that $\text{Re}(\beta/k_0)$ decreases steadily with the increasing slit width, while increases with the increasing dielectric constant ϵ_d . Thus, once the structure is already constructed, we can only actively modulate phase retardation by varying the dielectric constant ϵ_d , which can be implemented with Kerr nonlinear media instead of dielectric medium in the slit, with a metal–nonlinear optical material–metal (M–NL–M) structure. Hence we can manipulate the phase retardation as well as output beam by varying the intensity of incident light.

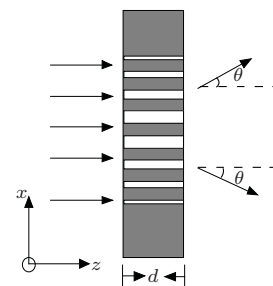


Fig. 1. Schematic layout of the M–NL–M structure studied. Here d is the thickness of nonlinear optical medium, planar wave incident normally from the left side, θ represents the splitting angle.

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The beam splitter modulator structure we proposed contains a planar thin Ag film and a nonlinear Kerr optical material featured with different nanoslit arrays, as sketched in Fig. 1. It is illuminated by normal light with TM polarized light under the excitation condition of SPPs. We choose the spacing between any two adjacent slits to be 400 nm, which is much larger than the skin depth of SPP mode at wavelength 850 nm.^[10] Therefore, the structure can be treated as the combination of several isolated M-NL-M structures. The dispersion relationship depicted in Fig. 2 can provide a way to design the desired phase retardation of each slit at weak incident light intensity. According to Fig. 2, we choose $d = 850$ nm, slit widths 50, 60, 70, 80, 110, 110, 80, 70, 60, 50 in sequence from top to bottom to obtain the original phase. Recently nonlinear optical medium can achieve a high value of third-order nonlinear susceptibility, e.g. $\chi^{(3)} \sim 10^{-6}$ esu,^[11] and a maximum peak power of incident light is just about 6.0 MW/cm². Therefore, we choose $\chi^{(3)} = 1.4 \times 10^{-7}$ esu $\approx 10^{-15}$ m²/V² for our simulation.

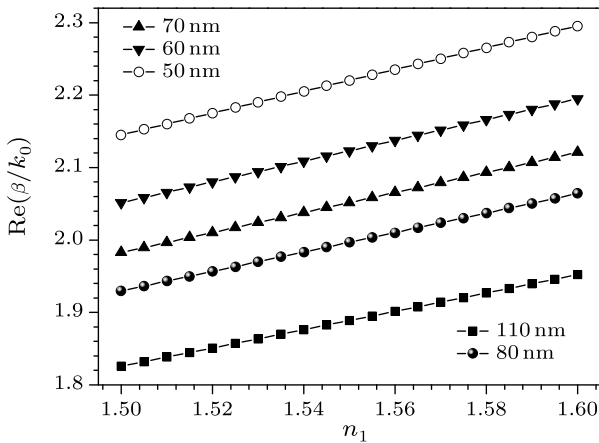


Fig. 2. Effective refractive index $\text{Re}(\beta/k_0)$ versus the dielectric constant ε_d at different slit widths: $w = 50, 60, 70, 80, 110$ nm with $\varepsilon_m = -32.217 + i1.726$ at the wavelength of 850 nm.

The modulation of splitting angle can be verified by a nonlinear two-dimensional finite difference time domain (FDTD) method.^[12] Figure 3 shows the simulation of electric-field intensity $|E|^2$ distribution of beam splitting with the structure. The splitting angle is indicated by white arrows. The electric-field amplitude of the incident light are $E = 1 \times 10^6$ V/m ($I \sim 0.133$ MW) in Fig. 3(a), and $E = 3.67 \times 10^6$ V/m ($I \sim 1.79$ MW) in Fig. 3(b). It is clear that when we change the incident light power from 0.133 MW to 3.67 MW, the angle is decreased. The modulation of splitting angle can be explained by the Fabry-Pérot resonance of SPPs in the nanoslits. When the slit is at the F-P resonance, the average electric field intensity $|E|^2$ in the slit is stronger than the slit-out of the F-P resonance, so the effective refractive index

increases greatly in the slit at the F-P resonance according to $\varepsilon_d = \varepsilon_0 + \chi^{(3)}|E|^2$. In Fig. 3(a), the slit with $w = 80$ nm achieves the F-P resonance when $E = 1 \times 10^6$ V/m, the phase retardation between slits of 80 nm and 110 nm is larger. When E grows to 3.67×10^6 V/m, the slit with $w = 110$ nm achieves the F-P resonance while the slit with $w = 80$ nm is out of the F-P resonance. Thus the added value of effective refractive index β/k_0 in the slit with $w = 110$ nm is larger than that in the slit with $w = 80$ nm, it makes a relative phase retardation smaller to decrease the splitting angle, as shown in Fig. 3. In fact, the changing of splitting angle is a quasi periodic action owing to the F-P resonance of SPPs in the nanoslit. We can periodically modulate the splitting angle from large to small with changing incident intensity. This makes the structure have comprehensive potential practical applications.

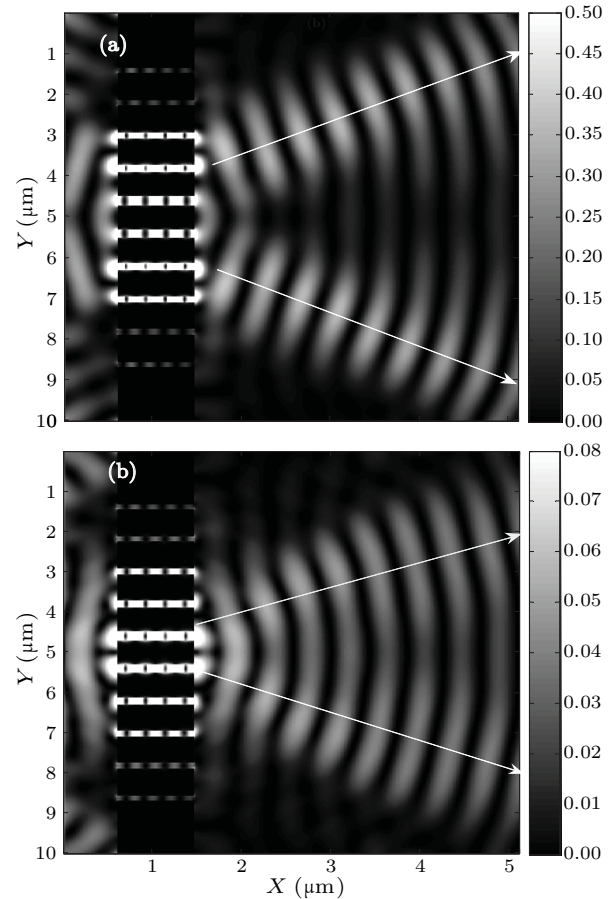


Fig. 3. The FDTD simulation of electric-field intensity $|E|^2$ distribution of beam splitting with the M-NL-M array structure. The parameters are as follows: the thickness of the Ag film is 850 nm, the distance between the two slits is 400 nm (centre to centre), the slit widths are 50, 60, 70, 80, 110, 110, 80, 70, 60, 50 nm from top to bottom. 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 $E = 1 \times 10^6$ V/m (a), $E = 3.67 \times 10^6$ V/m (b). The splitting angle is indicated by white arrows.

In conclusion, we have investigated an all-optical device based on an M-NL-M structure. Embedding nonlinear media in the slit region can be used to modulate the output beam efficiently as demonstrated above. The simulated results clearly show that the splitting angle can be controlled easily by the intensity of incident light. By analysing the properties of the splitting beam modulation, we explain the effects by the theory of Fabry–Pérot resonance of SPPs in the nanoslit. Because the whole element is formed on a planar thin film, this study is significant for miniaturization and integration of optical devices.

References

- [1] Barnes W L, Dereux A and Ebbesen T W 2003 *Science* **424** 82
- [2] Ozbay E 2006 *Science* **311** 5758
- [3] Bozhevolnyi S I, Volkov V S, Devaux E, Laluet J and Ebbesen T W 2006 *Nature* **440** 508
- [4] Porto J A, Martín-Moreno L and García-Vidal F J 2004 *Phys. Rev. B* **70** 081402
- [5] Min C J, Wang P, Jiao X J, Deng Y and Ming H 2007 *Opt. Express* **15** 9541
- [6] Smolyaninov Igor I 2005 *Phys. Rev. Lett.* **94** 057403
- [7] Wurtz G A, Pollard R and Zayats A V 2006 *Phys. Rev. Lett.* **97** 057402
- [8] Xu T, Wang C T, Du C L and Luo X G 2008 *Opt. Express* **16** 4753
- [9] Maier S A 2007 *Plasmonics: Fundamentals and Application* (Berlin: Springer)
- [10] Raether H 1988 *Surface Plasmons on Smooth and Rough Surfaces and on Gratings*(Berlin: Springer)
- [11] Liao H B, Xiao R F, Fu J S, Yu P, Wong G K L and Sheng P 1997 *Appl. Phys. Lett.* **70** 1
- [12] Taflove A and Hagness S 2000 *Computational Electrodynamics: The Finite-Difference Time-Domain Method* 2nd edn (Boston, MA: Artech House)