

Splitting and focusing of light with metal nano-slits coated with nonlinear Kerr medium

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We demonstrate that a finite number of nano-slits can realize beam splitting and focusing of light by coating the metallic film surfaces with nonlinear Kerr medium. The numerical simulation shows that the beam splitting and focusing can be controlled by the incident light intensity. The splitting angle is quasi-periodically modulated by the incident light intensity, and the focusing length of forward propagating transmitted light decreases as the incident light intensity increases. These effects are explained by the surface plasmon polariton Bloch modes and self-focusing theory.

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Since the discovery of extraordinary transmission phenomena of light through sub-wavelength hole arrays^[1], there has been renewed interest in the optical properties of sub-wavelength metallic structures. A series of optical phenomena, such as beaming, nano-focusing, splitting, and nano-guiding of light, have been demonstrated theoretically and experimentally^[2–6]. These phenomena have triggered an explosion of interest in sub-wavelength structure for designing new types of metallic nano-optic devices and miniaturization of photonic circuits^[7–9]. A great challenge that faces sub-wavelength metallic grating structure research has achieved active control of plasmonic signals in nano-optic devices^[10]. Recently, nonlinear optical devices based on sub-wavelength metallic structures have been proposed to actively control plasmonic signals^[11–14], which has great potential applications.

Previously, Min *et al.* reported an all-optical switching structure based on a sub-wavelength metallic grating containing nonlinear optical materials, which showed bistable behavior and resulted in a significant switch effect^[15]. In this letter, we report another function: beam splitting and focusing of such a metallic sub-wavelength structure by taking into account of the Kerr nonlinearity and Lorentz dispersion of nonlinear medium. The structure is simple and consists of a finite number of metal nano-slits coated with nonlinear Kerr medium, which can actively control the splitting angle and focusing length of output beam by the intensity of incident light, owing to the nonlinear response.

Figure 1 is a schematic illustration of the structure. It consists of a 1.2- μm -thick silver film with equal slit interspacing of 1.0 μm (center to center) and slit width of 0.4 μm . A TM-polarized plane wave with wavelength of 1.55 μm is normally incident onto the structure from the left side. We investigate a freestanding slit grating (SG) consisting of three nanoslits. Although electromagnetic waves transmitted from a sub-wavelength slit diffract in all directions, the slits array structure can enhance transmission and channel the beam into a narrow spatial re-

gion, as shown in Fig. 2. It is believed that surface plasmon polariton (SPP) Bloch modes play a major role in the phenomenon^[16]. At the metal-dielectric interface, the SPP is the wave propagating along the interface with the wave vector^[17,18]

$$\mathbf{k}_{\text{SPP}} = \mathbf{k}_0 \sqrt{\frac{\varepsilon_d \varepsilon_m}{\varepsilon_d + \varepsilon_m}}, \quad (1)$$

where \mathbf{k}_0 is the wave vector of incident wave, ε_d is the permittivity of dielectric, and ε_m is the permittivity of metal. Thus, once the structure is already constructed, we can actively modulate SPP excitation wavelength by varying the dielectric constant ε_d , which can be implemented with Kerr nonlinear medium instead of dielectric medium adjacent to the metal slit grating.

Now we study the structure consisting of a slit grating coated with nonlinear Kerr medium. Our finite difference time domain (FDTD) simulation shows that even this simple structure can present interesting optical properties. In the simulation, Drude model $\varepsilon_m(\omega) = \varepsilon_\infty - \omega_p^2/(\omega^2 + i\gamma\omega)$ with $(\varepsilon_\infty, \omega_p, \gamma) = (1.99, 1.35 \times 10^{16} \text{ rad/s}, 9.62 \times 10^{13} \text{ rad/s})$ was applied to fit the dielectric constant of metal silver^[19]. Following Ziolkowski's work^[20], the FDTD method treats the nonlinear effect with a finite response time as well as instantaneous manner by solving the phenomenological susceptibility equation together with Maxwell's equation:

$$D = \varepsilon_L \varepsilon_0 E + P^L + P^{\text{NL}}, \quad (2)$$

$$P^{\text{NL}} = \varepsilon_0 \chi^{\text{NL}}(|E|^2)E, \quad (3)$$

$$\frac{\partial \chi^{\text{NL}}}{\partial t} + \frac{1}{\tau} \chi^{\text{NL}} = \frac{1}{\tau} \varepsilon_2 E^2, \quad (4)$$

where P^L represents the Lorentz polarization and P^{NL} denotes the nonlinear polarization, ε_L is the linear relative permittivity, χ^{NL} is the nonlinear susceptibility, τ is the response time, and ε_2 is the Kerr model permittivity. The corresponding parameters are chosen as $\tau = 2 \times 10^{-15} \text{ s}$, $\varepsilon_2 = 2 \times 10^{-16} \text{ m}^2/\text{V}^2$. It is well known

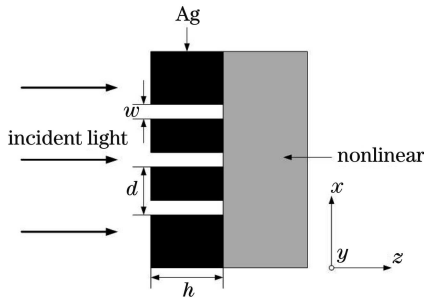


Fig. 1. Schematic of a metallic film coated with nonlinear medium. d is the distance between two adjacent slits, w is the slit width, and h is the film thickness. A TM-polarized plane wave is normally incident from the left side.

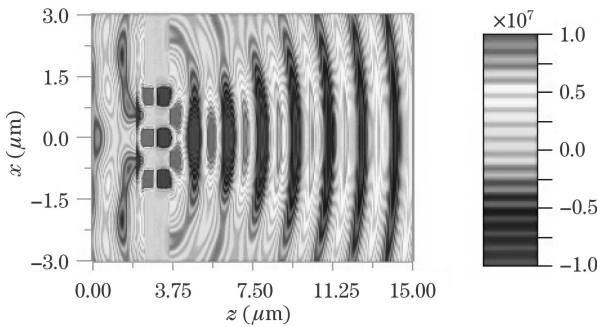


Fig. 2. FDTD simulation of optical intensity distribution of freestanding metallic grating with $h = 1.2 \mu\text{m}$, $d = 1.0 \mu\text{m}$ (center to center), $w = 0.4 \mu\text{m}$, and the wavelength of incident light is $\lambda = 1.55 \mu\text{m}$.

that dielectric constant ϵ_d in Kerr nonlinear media depends on the intensity of the electric field $|E|^2$:

$$\epsilon_d = \epsilon_1 + \chi^{\text{NL}} |E|^2, \quad (5)$$

where ϵ_1 is the linear dielectric constant. The Lorentz dispersion of the Kerr medium is considered and we get

$$\epsilon_1 = \epsilon_\infty + \frac{\omega_0^2}{\omega_0^2 - \omega^2 + i\Gamma\omega}, \quad (6)$$

where ϵ_∞ is the background permittivity, ω_0 is the resonant frequency, and Γ is the damping coefficient ($\Gamma \ll \omega$). In what follows, the parameters are chosen to be $\epsilon_\infty = 2.72$, $\omega_0 = 1.88 \times 10^{15}$ rad/s.

Figure 3 shows the FDTD simulation of optical field intensity distribution (H_y) of light emission from the nonlinear Kerr medium structure. The effect of beam splitting is clearly demonstrated. The emitted beam is formed by two side lobes and one transmitted forward propagation light. The field amplitudes of the incident light are $H_y = 5 \times 10^5$ V/m ($I \sim 4.72 \text{ GW/cm}^2$) in Fig. 3(a), $H_y = 7 \times 10^5$ V/m ($I \sim 9.25 \text{ GW/cm}^2$) in Fig. 3(b), and $H_y = 1 \times 10^6$ V/m ($I \sim 18.8 \text{ GW/cm}^2$) in Fig. 3(c), respectively. It is clear that when the incident light power increases, the splitting angle of two side lobes decreases, and the focusing length of forward propagating light becomes smaller. The splitting of emitted light can be explained by the excitation and coupling of SPP Bloch modes to transmitted photons. The SPP modes are coupled into transmitted light when diffraction from grating structure provides the momentum conservation

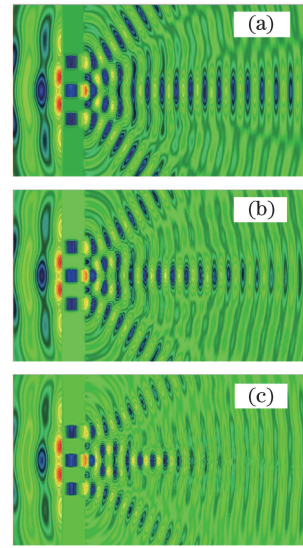


Fig. 3. Optical intensity distribution of metallic grating coated with nonlinear medium. The optical intensities of the incident light are (a) 4.72, (b) 9.25, and (c) 18.8 GW/cm^2 .

$k \sin \theta = k_{\text{SP}} \pm n2\pi/d$, where $k \sin \theta$ is the in-plane component of wave vector of the transmitted light, and n is an integer. From Eq. (5), when the incident light power increases, the effective refractive index of the grating increases, therefore, the SPP excitation wavelength decreases according to Eq. (1). Hence increasing the intensity of incident light results in the excitation of high-order diffraction modes which thus leads to the splitting of transmitted beam. In fact, changing splitting angle is a quasi periodic action owing to the excitation of higher order SPP modes. We can periodically modulate the splitting angle from small to large with changing the incident intensity. This makes the structure have comprehensive potential practical applications.

The modulation of focusing length of forward propagating transmitted light can be explained by self-focusing of Kerr medium^[21]. In order to see the self-focusing effect, the self-focusing action must be strong enough to overcome the diffraction action. If the two actions contend with each other, then the beam would propagate without any change of its spatial profile. This is the case of self-trapping. However, a small increase or decrease of the beam intensity would upset the balance for self-trapping and make the beam self-focus or diffract. We find that for our scheme, when the field intensity is $I = 4.72 \text{ GW/cm}^2$, the forward propagating transmitted light is self-trapped because the self-focusing cancels with the diffraction. When the field intensity grows from 4.72 to 9.25 GW/cm^2 , the beam appears to focus because the self-focusing overcomes the diffraction. When the intensity of incident light further increases to 18.8 GW/cm^2 , the focusing length decreases to about 3.5 μm . Previous studies on the ablation threshold for silver in the picosecond regime provide values of about 0.5 J/cm^2 and above^[22], only weakly depending on the pulse duration. For an intensity of 20 GW/cm^2 , fluences in the range from 0.1 to 0.5 J/cm^2 correspond to pulse durations from 5 to 25 ps. Therefore, ablation of the silver

films will not be critical for the considered parameters. Hence we can manipulate the focusing length of forward propagating transmitted beam by varying the intensity of incident picosecond laser.

In conclusion, we numerically demonstrate the directionality control of light from sub-wavelength slits in metallic film coated with nonlinear Kerr medium. The phenomena of beam splitting and focusing are simulated using a nonlinear FDTD method. The results clearly show that the splitting angle can be actively controlled by the intensity of incident light. We explain the effect by the excitation and coupling of SPPs along the interface of metal-nonlinear medium. By analyzing the properties of the focusing length modulation of forward propagating transmitted beam, we explain the effect by the theory of self-focusing of the Kerr medium. Because the structure is simple and the whole element is formed on a planar thin film, this study is significant for miniaturization and integration of optical devices. Compared with conventional metallic arrays, this structure can actively control the direction of emitted light, which has great potential applications in optical data storage, nanoscale directional light sources and emitters.

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