Manipulating optical polarization by stereo plasmonic structure

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Abstract: We theoretically study a particular plasmonic structure with stereo nanoholes array in metallic film, which has remarkable abilities to manipulate the optical polarizations at optical frequencies. The main property is that any linear polarization states including a complete 90° optical rotation can be obtained in transmission by proper structural design in combination of enhanced transmission efficiency. Together with the polarization change, surface plasmon propagation bounded on the surface of transmission side also can be modulated. Furthermore, an analytical Coupled Mode Method (CMM) is developed by introducing a frequency dependent coupling coefficient to describe such optical rotation property in stereo plasmonic systems.

OCIS codes: (260.5430) Polarization; (240.6680) Surface Plasmons; (260.3910) Metals, optics of.

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1. Introduction

Optical activity, the property of materials to rotate the polarization plane of linear polarized light, has attracted much attention in history. In natural materials like quarts [1], optical activity is usually very weak as a consequence of molecular electric and magnetic polarization coupling. The recently emerging concept of metamaterial, by utilizing artificially trimmed metallic structures in subwavelength scale, opens up the possibility to achieve giant electromagnetic (EM) response in optical frequency region, and therefore inspired new ways to enhance and expand optical activity effects. The mainstream of this artificial optical activity is chiral metamaterials with helix structures for their scientific novelty [2,3], and probable application within optical region [4,5]. Another type of design is to use planar metamaterials [6,7] to realize polarization control, taking advantage of their broken symmetry and coupling effects. However, these artificial metallic 'atoms' always accompany great absorption with respect to these polarization controlled modes, which are revealed as the transmission minimums and forbid the transmitted far-field to be further utilized.

Inspired by the extraordinary optical transmission (EOT) effect associated with the surface plasmon polariton (SPP) excitations on metal surfaces [8–10], several approaches have been carried out to achieve optical activity by drilling special holes or grooves in metallic films based on particular plasmonic excitations [11–15] or similar mechanism in THz region [16,17]. However, more effective and fruitful manipulation still remains challenges, especially in optical frequency. In this paper, we theoretically proposed a design of stereo-shaped nanoholes array drilled in metallic film, to bring the EOT effect to realize an efficient optical polarization control at will. Our numerical results definitely show that this structure can be designed to arbitrarily rotate the polarization states in optical transmissions for certain linearly polarized incidence. The excellent optical rotation modes are manifested as transmission peaks endowing our structure as an ultrathin polarization rotator. On the other hand, this SPP associated polarization change in the transmission side surface results in a change of surface wave propagation, which also indicates possible applications in future integrated optics. Moreover, we developed a commonly used Coupled Mode Method (CMM) [18,19] by introducing a frequency dependent conductive coupling coefficient, so that it gives a way in which CMM can be expanded to work in stereo plasmonic systems, as well as to provide a clear understanding of the mechanism of such efficient optical rotation. Good agreement with the numerical simulations indicates the validation of our developed analytical method.

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2. Modeling and numerical approaches

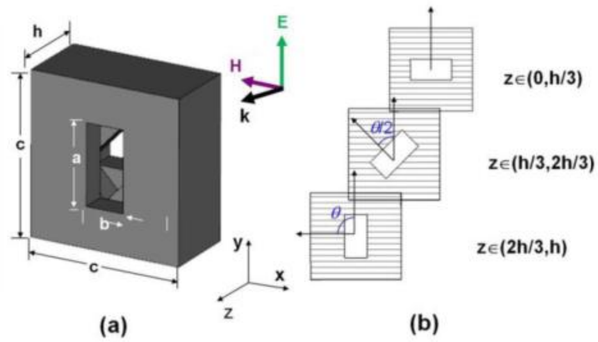

Fig. 1. (a) Unit cell of proposed stereo plasmonic waveguide array with structural parameters of a=300nm, b=150nm, c=600nm, h=300nm, and θ=90°. (b) Cross section of stereo structure at three layers respectively.

For simplicity, the proposed structure is modeled as a freestanding metal film perforated with stereo-shaped nanohole array. The unit cell for a certain example is schematically shown in Fig. 1(a), where the structure contains three metallic layers with the rectangular holes differently orientated within each layer, as the sectional views depicted in Fig. 1(b). Geometric parameters are marked in Fig. 1(a) as in-plane period is c=600 nm, total thickness is h=300 nm, and hole dimensions are a=300 nm and b=150 nm. Principal axes of the rectangular holes in next layer rotate for an angle of $\theta/2$, thus the total rotation angle is θ.

Numerical simulations are performed by commercial software CST Microwave Studio using Finite Integration Method. The metal material is defined as gold with complex permittivity described by the Drude mode $\varepsilon=1-\omega_p^2/(\omega^2 + i\omega\gamma)$, whose plasma frequency is $\omega_p=1.37\times10^{16}$ *rad/s* and collision frequency is $\gamma=12.24\times10^{13}$ *rad/s*, considering the increased loss in the nanoscale system [20,21]. To be noted this definition is used in the following analytical approach. Periodic boundary conditions are set in x and y directions, representing the periodically arranged nanohole array. Incidence is an electrically y-polarized plane wave propagating along + z direction and hence, the boundary condition in z direction is set as open. Probes along x and y directions are located 3μm from the structure to detect the transmission components of different polarizations, at which position the transmitted electromagnetic field has already been uniform within concerned frequency range, because the sample is a subwavelength structure and the diffraction effect in far field area is well prohibited.

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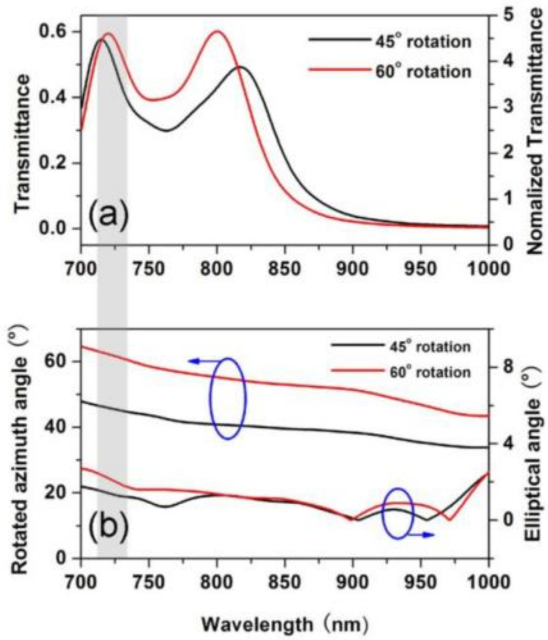

Fig. 2. Numerical result of polarization control of stereo structures with different rotation angles of 45° and 60°. (a) Transmission spectra with polarization perpendicular to long axis of last layer. (b) Spectra of the corresponding rotated azimuth angle and ellipticity angle.

From simulation results, our structures show the ability to arbitrarily rotate the polarization state to any direction by carefully designing the stereo holes. For examples, in cases of structures with total rotation angles equal 45° and 60°, Figs. 2(a) and 2(b) give the spectrum of transmission intensity with polarization along the designed 45° and 60° direction under *y*-polarized illuminations, as well the their rotated azimuth angle and ellipticity. Relative strong optical transmittances are clearly observed as two peaks at wavelength of about 720 and 800 nm. When normalized to the nanohole occupation area, the transmittances are greatly higher than one unit, indicating an enhancement effect. Moreover, the optical rotation modes of about 720 nm are almost independent of structures, which are well reflected from the transmission peaks and good matches to the desired rotation angle for these 45° and 60° samples [see Fig. 2(b)]. Both of them exhibit good linearity (elliptical angles < 4°) in transmissions within the spectra we concerned. It is reasonable that we also can obtain a corresponding rotated polarization state about 720 nm wavelength for any other rotated structure. This means a fully control of transmitted polarization will be accomplished. In the following, we will elaborately show the result of 90° rotation structure (shown in Fig. 1), which is expect to achieve a totally polarization conversion from vertical to horizontal.

Figure 3(a) illustrates the polarized transmission spectra in the original (T_{yy}) and it orthogonal (T_{yx}) polarization states when a *y*-polarized light incident onto a 90° rotation structure (*h*=300nm), in which both complete polarization conversion (because T_{yy} are almost zero) and about 70% maximum transmittance (T_{yx}) are observed belonging to this polarization conversion. Split transmission peaks are considered from the plasmonic coupling between two metal surfaces [22]. Peak shift with respect to the metal film thickness given in Fig. 3(b) provides positive support that thicker metallic layer (from 150 to 450nm) reduces coupling strength and hence decrease peak gap. Field distributions of peak modes are shown in Fig. 3(c), and in phase and out-of phase coupling between SPPs give rise to splitting of peaks (marked as

① and ②). Incidentally, new peak in smaller wavelength (658nm) for the large thickness case (h = 750nm) is found corresponding to Fabry-Perot (F-P) cavity mode due to the elongated hole channel to meet a certain resonance condition, which is well reflected from the strong field concentrated inside the twisted nanohole channel. Detailed field distributions for these modes are shown in Fig. 3(c).

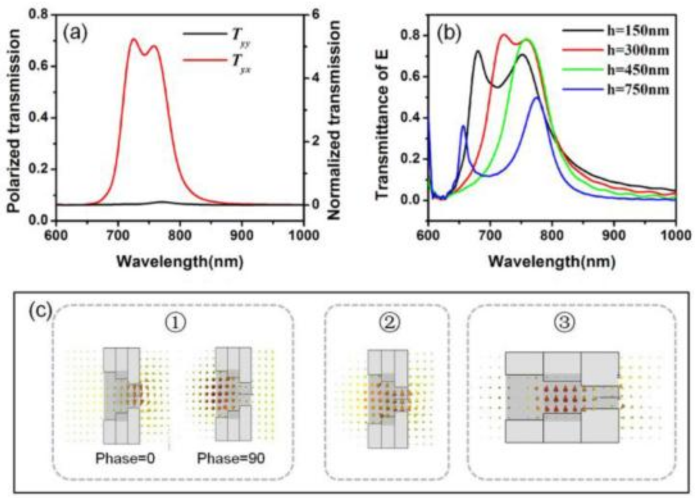

Fig. 3. Numerical results of transmission properties for 90° rotation structure. (a) Transmission spectra detected in x- and y-polarization under y-polarized incidence (here h=300nm). (b) Transmittance of E_x for different total thicknesses, as h=150nm, 300nm, 450nm, 750nm, respectively. (c) E field Distributions of distinct modes marked out in (b).

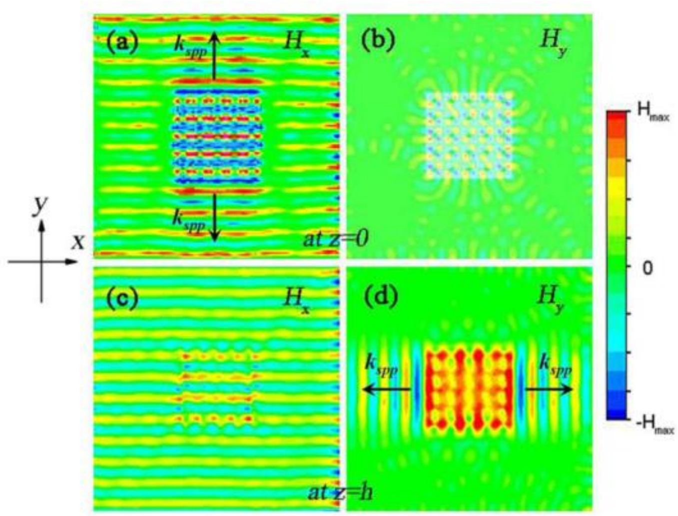

Fig. 4. Magnetic field distributions on the metal surfaces of a stereo structure containing 5×5 period array with h=300nm and θ=90° at λ=769nm: (a) H_x and (b) H_y at incident side z=0, (c) H_x and (d) H_x at transmission side z=h, where H_{max}=0.002A/m.

Another important feature of this stereo plasmonic structure is the ability to change the propagation of SPP waves bounded on the metal surface of transmission side. It is verified by surface field distributions in Figs. 4(a)-4(d) from the sample of h=300 nm, where an excited SPP wave along ±y directions on the incident surface (z=0), corresponding to a y-polarized incidence, is transferred to propagating along ±x directions on the transmission surface (z=300 nm) (all are indicated by the magnetic field components). This phenomenon explains that near-field polarization rotation effect causes SPP propagation change. In this sense, this structure also acts like a polarized coupler that can couple the far field incidence into a modulated propagation SPP wave, further implying it to have promising application in photonic integrations.

3. Analytical approach and discussions

In this section, we will focus on the underlying physics of such polarization control by this stereo plasmonic structure. The mechanism of this polarization manipulation is obvious different the natural optical activities, in which coupling effect between electric and magnetic dipoles results in a non-diagonalized susceptibility tensor. Then, our structure cannot be described by effective EM parameters (ε and μ) like the metamaterial, mostly due to the light (EM field) can only touches the first layer and the responses of the inner layers mainly arises from the plasmonic coupling. Although numerical results have provided us the major phenomena and intuitive explanations, it is necessary to explore this structure in more scientific sense within the framework of plasmonic EOT system.

Previous studies [9,10] have given out two eigen modes for single layer structures containing rectangular hole array, which are reasonably regarded as linear polarized parallel and perpendicular to the long axis of the hole, respectively. Due to the twisted shape of nanohole, this diffusion current brings a partially matched conductive coupling between adjacent layers. Base on this, we developed the analytical method- Couple Mode Method (CMM) that widely employed in deducing the EOT phenomena [18,19] - to be applied in our complex stereo structure [see Fig. 5(a)]. According to CMM, fields in each section can be expanded by Fourier series with respect to reciprocal vectors, and these coefficients can be determined by solving the boundary conditions. However, stereo structure has too complicated boundary conditions to be analytically solved. So we attempt to some reasonable approximations in order to simplify this problem.

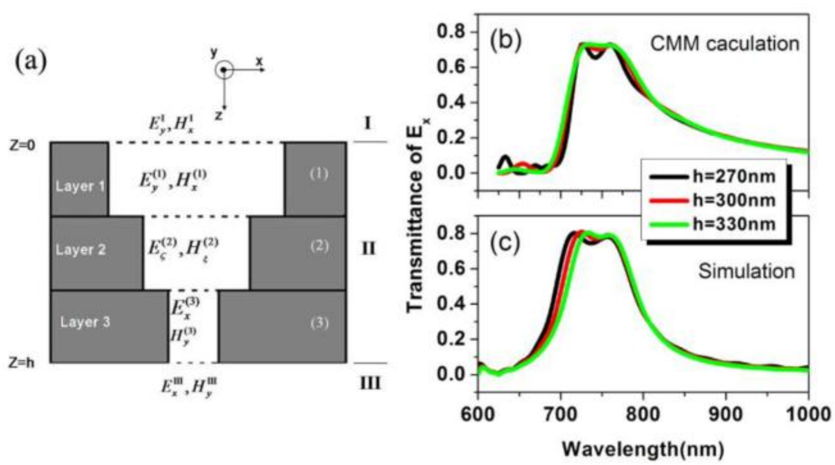

Fig. 5. (a) Cross section of 3D stereo structure at plane of y=0 and demonstration of notation in calculation via developed Coupled Mode Method. Transmittance spectra of E_x calculated by (b) developed Coupled Mode Method and (c) numerical simulations, for three samples with total thickness of h=270nm, 300nm, and 330nm.

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We make an approximation that only the strong mode of the next layer (E field perpendicular the long axis of hole) is excited by the front layer due to the neglectable contribution of another mode (E parallel to the long axis) in transmissions [10]. Then, mode in the next layer is proportion to its front layer by multiplying a coupling (or energy transferring) coefficient η, whose expression will be discussed in detail below. Under the framework of traditional Coupled Mode Method, fields in section I, III can be expanded by summing over the plane waves with wave vectors integer times of the inversed periodicity. In this analytical model, we define the incident light is y-polarized (E//y-axis), in coincidence with former numerical simulations as well as the selection of strong plasmonic mode for rectangular holes. Specifically, fields in region I and III [see Fig. 5(a)] can be of the following form as

$$H_x^{\mathrm{I}} = e^{ik_0 z} + \sum_m R_m e^{ik_0(\kappa_m y - \lambda_m z)}, E_y^{\mathrm{I}} = -\frac{\mu_0 c}{\varepsilon_1}[e^{ik_0 z} + \sum_m \lambda_m R_m e^{ik_0(\kappa_m y - \lambda_m z)}], \tag{1a}$$

$$H_y^{\mathrm{III}} = \sum_n T_n e^{ik_0[\gamma_n x - \chi_n(z-3h)]}, E_x^{\mathrm{III}} = -\frac{\mu_0 c}{\varepsilon_3}\sum_n \chi_n T_n e^{ik_0[\gamma_n x - \chi_n(z-3h)]}, \tag{1b}$$

where $\kappa_m = m\frac{2\pi}{ck_0}$, $\lambda_m^2 = \frac{\varepsilon_1}{k_0^2} - \kappa_m^2$, $\gamma_n = n\frac{2\pi}{ck_0}$, $\chi_n^2 = \frac{\varepsilon_3}{k_0^2} - \gamma_n^2$. ($c$ is the periodicity), m=0,1…, and only the orthogonal field (H_y and E_x) are expressed in region-III considering field rotation effect. It should be noted that for this particular polarization incidence, only modes with y-directional reciprocal vectors can be excited in region-I, then the summation over reciprocal vectors in x-direction is eliminated in Eq. (1a). Correspondingly, the fields in region-III are supposed to convert to the orthogonal directions and only expansion in x-direction is considered in Eq. (1b). Under a simplified approximation with the energy transferring coefficient (η), we can obtain the rotated fields in holes of each layer in region-II in their principal coordinate (ζ, ξ along the long and short sides of rectangular holes respectively) systems

$$H_\xi^{(1)} = \cos k_x x \cos k_y y (Ae^{ik_z z} + Be^{-ik_z z}),\ E_\varsigma^{(1)} = -\mu_0 c\sigma \cos k_x x \cos k_y y (Ae^{ik_z z} - Be^{-ik_z z}) \tag{2a}$$

$$H_\xi^{(2)} = \eta H_\xi^{(1)},\ E_\varsigma^{(2)} = -\eta E_\varsigma^{(1)} \tag{2b}$$

$$H_\xi^{(3)} = \eta^2 H_\xi^{(1)},\ E_\varsigma^{(3)} = \eta^2 E_\varsigma^{(1)} \tag{2c}$$

where $\sigma=(k_0/k_z)(1-k_x^2/k_0^2)$, and we have the dispersion of

$$\tan\frac{k_x a}{2} = \frac{k_0}{ik_x\sqrt{\varepsilon_m}},\ \tan\frac{k_y b}{2} = \frac{k_0}{ik_y\sqrt{\varepsilon_m}}, \text{ and } k_z = \sqrt{k_0^2 - k_x^2 - k_y^2}, \tag{3}$$

according to the boundary condition in holes define by the size a and b, and only the zeroth mode is considered.

Now we come back to find out a proper form of η. Since our assumption to achieve the field in different layers is simply by multiplying this coefficient, η must be a complicated function of k_z and in a reasonable form of $\eta(k_z)=\eta_0[\exp(ik_z h)+const]$, where k_z is responsible for the phase component. For simplicity, we expand $k_z(\omega)$ to 1st order approximation in the neighborhood of ω_0,

$$k_z(\omega) = k_{z0} + \frac{\partial k_z}{\partial \omega}\Big|_{\omega=\omega_0}(\omega-\omega_0) + ..., \tag{4}$$

where ω_0 is a parameter correlated with thickness h, hence we get the form of η as

$$\eta(\omega) = \eta_0[e^{-C(\omega-\omega_0)}e^{iD(\omega-\omega_0)} + c], \tag{5}$$

where parameters C and D are real and defined as $\frac{\partial k_z}{\partial \omega}\Big|_{\omega=\omega_0} \cdot h = D + iC$. To determine unknown parameters A and B in Eqs. (2a)-(2c), following boundary conditions are applied.

$$H_x^{\mathrm{I}}\big|_{z=0} = H_x^{(1)}\big|_{z=0}, \quad H_y^{\mathrm{III}}\big|_{z=h} = H_y^{\mathrm{II}}\big|_{z=h}, \tag{6a}$$

$$E_y^{\mathrm{I}} + ZH_x^{\mathrm{I}}\big|_{z=0^-} = E_y^{(1)} + ZH_x^{(1)}\big|_{z=0^-}, \quad E_x^{\mathrm{III}} - ZH_y^{\mathrm{III}}\big|_{z=h^+} = E_x^{\mathrm{II}} - ZH_y^{\mathrm{II}}\big|_{z=h^+}, \tag{6b}$$

where Z is the notation of surface impedance of metal as $Z = \mu_0 c / \sqrt{\varepsilon_m}$. It is essential to find that fields in former layers combine together to work on the boundary conditions

$$E_x^{\mathrm{II}} = E_\xi^{(2)}\big|_{z=h} + E_\xi^{(3)}\big|_{z=h} \times \cos(\frac{\theta}{2}), \quad H_y^{\mathrm{II}} = H_\varsigma^{(2)}\big|_{z=h} + H_\varsigma^{(3)}\big|_{z=h} \times \cos(\frac{\theta}{2}), \tag{7}$$

where θ equals to 90° for these polarization conversion cases. By solving Eqs. (6)-(7), zeroth ordered transmission is calculated in the following form as [19],

$$T = \left|t_0 F(\lambda)\right|^2, \tag{8}$$

where the parameters are defined as

$$t_0 = \frac{4w\sigma}{(1+\varepsilon_m^{-1/2})^2}, \ F(\lambda) = \frac{\eta(\lambda)}{\frac{e^{-ik_z h'}}{\delta^+} + \frac{e^{ik_z h'}}{\delta^-}} \cdot \frac{1}{(1-\theta^+)(1+\theta^-)}, \tag{9a}$$

$$\delta^{\pm} = \eta(\lambda) + \frac{1}{\sqrt{2}}e^{\pm ik_z h'}, \quad \theta^{\pm} = \frac{\sigma \pm \varepsilon_m^{-1/2}}{\sin ck_y b}\sum_m \frac{wt_m h'_m}{\lambda_m + \varepsilon_m^{-1/2}}, \quad h' = \frac{h}{3}. \tag{9b}$$

Figure 5(b) gives the results of polarized transmittance of field E_x with our method for thicknesses of 270nm, 300nm and 330nm, which show good agreement with the simulated results [see Fig. 5(c)] both in peak positions and the splitting evolution with respect to the total thickness. The fitting parameters in coupling coefficient η in form of Eq. (5) are: (a) ω_0=675THz, C=35 and D=135 for h=270nm; (b) ω_0=653THz, C=25 and D=100 for h=300nm; (c) ω_0=633THz, C=21 and D=82 for h=330nm, and *const*=2.3, η_0=0.1 are constants for all thicknesses. Therefore, this developed Coupled Mode Method is valid to deal with this stereo structure, and indicates more applications in some other similar complicated plasmonic system.

From the analytical approach, we may find the contribution of the periodicity is revealed in Eq. (1) when the reflected and transmitted field are expanded to the plane waves with respect to the reciprocal vectors κ_m, while the influence of the hole shape is related to the in-plane k vectors with a metal permittivity related dispersion [see Eq. (3)], which was usually considered as a shape resonance [9] or cavity plasmonic mode [19]. The periodically modulated SPP and localized shape plasmonic mode act as the collector to arrest the majority of energy of proper incident wave. Another major contribution is the twisted hole channel, as interpreted as conductive coupling coefficient η [Eq. (5)], which plays the major role to rotate the polarization state of field and even to reradiate in the transmission side with the aid of SPP and shape resonance on the other side. Thanks to the mixed contribution of these factors, an efficient polarization rotation together with relative strong transmission intensity is achieved even for arbitrary rotation angle at will.

4. Conclusions

A kind of stereo plasmonic structure is theoretically proposed and intensively studied in this paper, which is proved to having strong ability in manipulating transmitted optical polarization as well as near field SPP propagation. Our numerical results reveal considerable strong polarized transmission intensity and versatile SPP mode associated with the coupling effect and F-P like cavity mode, which all contribute to such an optical rotation property. It is rightly due to this particular stereo-hole design that breaks the mirror symmetry of the structure and gives rise to the partially matched coupling for the plasmonic modes between layers. Based on this mechanism, we developed the Coupled Mode Method by introducing a frequency dependent coupling coefficient so as to analytically deal with this stereo plasmonic system. Besides the scientific contribution, this kind of stereo plasmonic system with good optical functionality suggests practical applications in nano-optics with the development of advanced fabrication technology.

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