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.

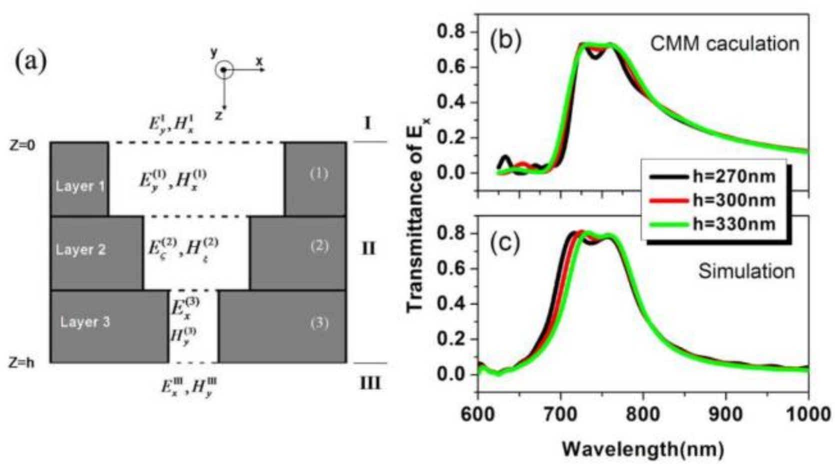

Fig. 5. (a) Cross section of 3D stereo structure at plane of y=0 and demonstration of notation in calculation via developed Coupled Mode Method. Transmittance spectra of E_x calculated by (b) developed Coupled Mode Method and (c) numerical simulations, for three samples with total thickness of h=270nm,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

#137855 - $15.00 USD Received 9 Nov 2010; revised 20 Dec 2010; accepted 22 Dec 2010; published 5 Jan 2011

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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