Subwavelength polarization rotators via double-layer metal hole arrays

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We show that the polarization of linearly polarized light can be rotated an arbitrary angle by double-layer metal hole array structures in a subwavelength regime. The transmitted light with the rotated polarization, however, remains of nearly the same strength as the incident field at particular frequencies. The mechanism can be attributed to the subwavelength feature of the rectangular holes, and the tangential guiding modes between layers modulated by the orientation of the holes. The structures have potential applications as polarization rotators in a broad frequency range covering from terahertz (THz) to infrared frequencies.

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The manipulation of optical activity of materials is a long standing issue in physics and attracts much attention in research. To achieve optical activity, one has to introduce materials of novel effective constitutive relations so that the mode conversion mechanism can be provided either from the bulk or the surfaces. Thus, chiral [1–6] and anisotropic [7–12] metamaterials can be used as efficient tools to control the polarizations of the electromagnetic wave.

In this work we present an efficient method to rotate the polarization of linearly polarized light based on the double-layer metal hole array structure [13–16]. The mechanism of the polarization rotation relies on the following two points: one is the subwavelength feature of the holes requiring the polarization of the transmitted field to relate with the orientation of the holes in the lower plate closely (we assume that the incident light propagates from the upper plate to the lower all through the presentation); the other is the tangential guiding modes [17] in the gap between the metal layers, which couple the holes in the upper and the lower metal plates. By arranging the orientations of the holes properly, the polarization of the incident field can be rotated 90 degrees after it passes through the structure. Interestingly, the strength of the transmitted field with the rotated polarization is nearly the same as that of the incident field at particular frequencies.

The structure under consideration is shown in Fig. 1(a). To characterize the orientations of the rectangular holes in the metal plates, the angles between their longer sides and the y-axis are denoted as θ for the ones in the upper plate and φ for those in the lower one. We denote the periodicity of the metal hole array as d. The longer sides of the rectangular holes are of the length $0.42d$ and the shorter sides are $0.09d$. The thicknesses of the two metal plates and the gap between them are $0.05d$. To get a feeling of the effect of the orientation of the holes, we first fix the angle $\theta = 0$ degrees (the longer sides of the holes in the upper plates are along the y-axis) and rotate the holes in the lower plate. The incident field with x-polarization normally shines on the upper metal plate. The transmission spectra for the cases $\varphi = 30$ degrees and $\varphi = 60$ degrees were calculated by the mode expansion method [18,19] and are shown in Fig. 1(b). It can be seen that the total transmission for each of the two cases (the blue and turquoise dash curves) has two peaks at frequencies much lower than the well known Wood's anomaly ($\omega d/c = 2\pi$). These two transmission peaks result from the tangential guiding modes traveling in the gap between the two metal plates [17]. At the resonant frequencies, the tangential wave vectors of the guiding modes are the same as that at Wood's anomaly, but the vertical dimension between the two metal plates can support additional bound modes, which cause the much lower peak frequencies. From the ratios of T_{xx} to T_{xy} around the resonance frequencies

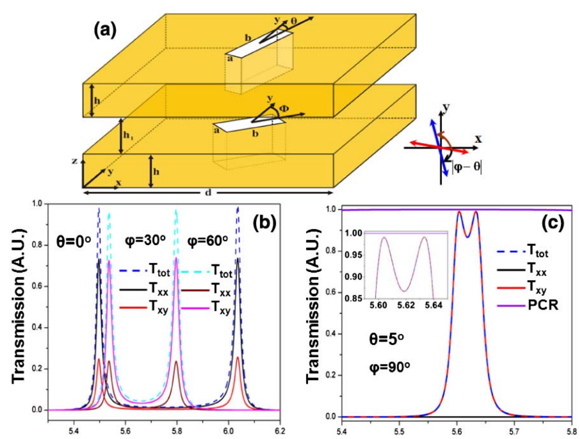

Fig. 1. (Color online) (a) Schematic illustration of the geometry of the double-layer metal hole array; in the inset (on the right side) the red arrow presents the polarization of the dominant mode in the upper hole, and the blue arrow shows the polarization of the dominant mode in the lower hole. The angle difference between them in clockwise direction is $|\theta - \varphi|$. (b) The transmission spectra for the cases $(\theta, \varphi) = (0°, 30°)$ and $(\theta, \varphi) = (0°, 60°)$: the blue (dash), black (solid) and red (solid) curves are for the case $(\theta, \varphi) = (0°, 30°)$, and the turquoise (dash), dark red (solid) and pink (solid) curves are for the case $(\theta, \varphi) = (0°, 60°)$. (c) The transmission spectra and PCR for the case $(\theta, \varphi) = (5°, 90°)$; the inset shows the details around the transmission peaks.

(high transmission), we can determine that the polarizations of the transmitted fields are perpendicular to the longer sides of the holes in the lower metal plate in both cases. This is due to the subwavlength feature of the holes, which means that the dominant mode existing in holes is the fundamental TE mode with its tangential electric field perpendicular to the longer sides of the holes [see the inset in Fig. 1(a)]. Consequently, the orientation of the holes determines the polarization of the transmitted field.

If the polarization of the dominant mode in the upper holes is perpendicular to that in the lower ones, the coupling between them would be killed, and there would be no transmission. Thus, we have to optimize the angle θ by fixing the value of φ as 90 degrees to achieve the largest polarization rotation. The transmission spectra and the polarization conversion ratio (PCR) $|T_{xy}|^2/(|T_{xx}|^2 + |T_{xy}|^2)$ for the optimal case $\theta = 5$ degrees are presented in Fig. 1(c). It shows that the polarization of the transmitted field is indeed rotated 90 degrees from that of the incident field, and the strength of it can be almost equal to that of the incident field at particular frequencies ($\omega d/c = 5.6041$ and $\omega d/c = 5.6332$). Another interesting observation is that there are two tangential guiding modes in such a small air gap (much smaller than half wavelength), while the original understanding predicts that there should be only one such mode [17]. Moreover, when the difference between θ and φ is larger, the frequency difference of the two transmission peaks becomes smaller (this should be clear by comparing the three cases shown in Fig. 1), indicating that the tangential guiding modes are modulated by the orientations of the holes in both the two metal plates.

To clarify the details of the tangential guiding modes and how the polarization is rotated, we calculated the tangential electric field (the vector field containing both the x and y components) in the gap for the case $\theta = 5$ degrees and $\varphi = 90$ degrees. The tangential electric field distributions on the x-y planes of different vertical distances from the lower surface of the upper plate (along the minus z-direction) are presented in Figs. 2 and 3 at the two peak frequencies. They illuminate that the two transmission peaks correspond to two different polarization-rotation channels, rotating the tangential field clockwise at the lower peak ($\omega d/c = 5.6041$) and anticlockwise at the higher peak ($\omega d/c = 5.6332$). Due to the influence of the subwavelength holes on the polarization of the light passing through them, the angle by rotating clockwise should be larger than that by rotating anticlockwise [20], which means that the clockwise rotation bears a larger phase difference. Thus, it explains why the mode rotating the tangential field clockwise locates at the lower frequency. As the difference between θ and φ becomes larger, the difference between the angle rotating clockwise and that rotating anticlockwise becomes smaller [20], which indicates the smaller frequency difference between the two transmission peaks.

Based on the double-layer metal hole array we proposed a polarization rotator in THz regime. Three μm-thick gold films with periodically perforated holes are fabricated on both sides of a 10 μm-thick parylene-C thin film by following the process flow shown in Fig. 4(a). The longer and shorter sides of the perforated rectangular holes are 65 and 15 μm, respectively, and the periodicity of the hole array is 150 μm. The tilting angles from the y-axis are still $\theta = 5$ degrees for the upper holes and $\varphi = 90$ degrees for the lower holes. In the designed frequency range, the metal can be modeled as perfect electric conductor (PEC), and the relative permittivity of parylene-C is 3 [21]. The calculated transmission spectra and PCR are shown in Fig. 4(c). Due to the larger relative permittivity of parylene-C, more tangential guiding modes can be supported in the gap, and thus three double-peak profiles are observed for T_{xy}. The polarization of the transmitted field is indeed rotated from the original x direction to y direction totally around the transmission peaks (PCR = 1). Remarkably, at the lowest resonant frequency (around 1 THz) the thickness of the polarization rotator (16 μm) is about 1/20 of the wavelength. This is much smaller than the thickness of the traditional half-wave plate. In our calculation, we do not consider the

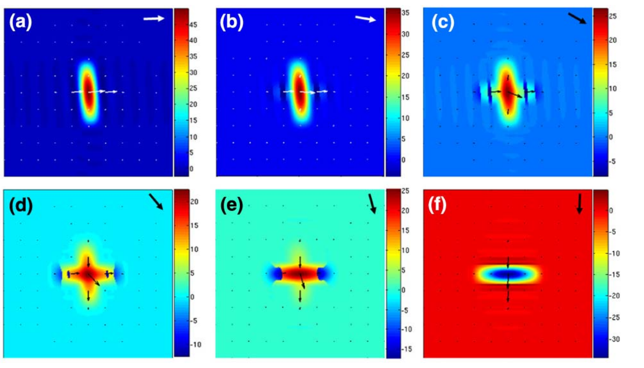

Fig. 2. (Color online) Tangential field distributions on the x-y planes at different vertical heights in the gap at $\omega d/c = 5.6041$: (a) on the lower surface of the upper plate $z = h + h_1$ ([the origin of the coordinate is defined in Fig. 1 (a)], (b) on the plane $z = h + h_1 * 4/5$, (c) on the plane $z = h + h_1 * 3/5$, (d) on the plane $z = h + h_1 * 2/5$, (e) on the plane $z = h + h_1/5$, (f) on the upper surface of the lower plate $z = h$. The smaller arrows in each figure present the directions of the local tangential fields, and the larger ones at the right up corners are to present how the tangential fields at the center point rotate.

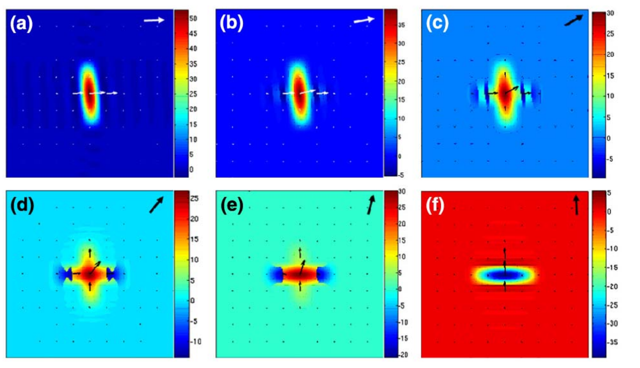

Fig. 3. (Color online) Tangential field distributions on the x-y planes at different vertical heights in the gap at $\omega d/c = 5.6332$: (a) on the lower surface of the upper plate $z = h + h_1$, (b) on the plane $z = h + h_1 * 4/5$, (c) on the plane $z = h + h_1 * 3/5$, (d) on the plane $z = h + h_1 * 2/5$, (e) on the plane $z = h + h_1/5$, (f) on the upper surface of the lower plate $z = h$. The smaller arrows in each figure present the directions of the local tangential fields, and the larger ones at the right up corners are to show how the tangential fields at the center point rotate.

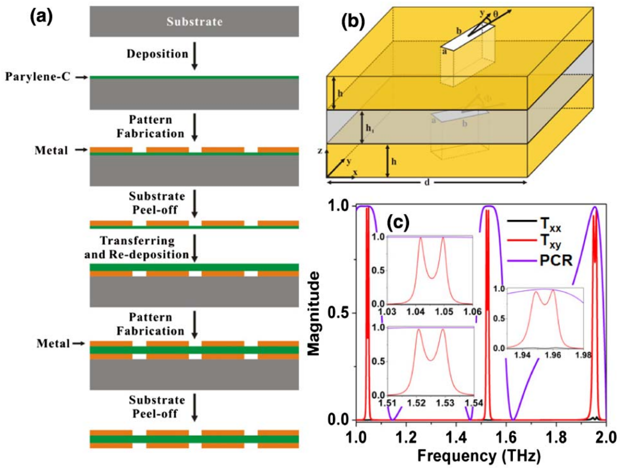

Fig. 4. (Color online) (a) Proposed process flow for the fabrication of the polarization rotator; (b) the schematic configuration of the polarization rotator: the shielded region denotes the Parylene-C thin film; (c) the transmission spectra and PCR: the insets show the details around the three double-peak profiles. PCR is almost 1 around the transmission peaks.

losses, but the realistic experiment results should not deviate very much due to the small losses from the metal and parylene-C [21] in the frequency range.

In conclusion, we proposed an efficient method to rotate the polarization of the linearly polarized light based on the double-layer metal hole array. The mechanism of the polarization rotation relies on the subwavelength feature of the holes and the tangential guiding modes in the gap between the two metal plates. The anisotropy of the subwavelength holes would help to reduce the thickness of the device. The tangential guiding modes between the plates enhance the coupling and thus provide better polarization rotation efficiency.

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