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High-Efficiency Wide-Band Cross-Polarization Conversion Using Bi-layered Metal Hole Pairs

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We present a polarization converter composed of bi-layered metal films perforated with rectangle hole pairs in each film. The proposed converter can convert the polarization of an incident linearly-polarized electromagnetic wave to its orthogonal direction with high efficiency and large bandwidth in the infrared or microwave regions. To make sure of the mechanism of polarization conversion, the current and electric-field distributions at different resonant frequencies are analyzed. It is found that the cross-polarized transmission is due to the near-field coupling between hole pairs in neighboring metal films. Finally, a prototype of the proposed converter is fabricated and measured in the microwave region. Good agreement between the experimental and simulated results is obtained.

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Polarization is an essential characteristic of electromagnetic waves, which has a wealth of applications in display, sensing, advanced communications, industry testing, and life microscopy.[1,2] To manipulate the polarization state of electromagnetic waves, polarization rotators or converters are often employed. The function of the polarization rotators and converters includes rotation of the polarization plane of incident electromagnetic waves and conversion between the linear polarization and elliptical/circular polarization.

Conventional rotators and converters such as half-wave and quarter-wave plates are mainly made of birefringent crystals or liquid crystals.[1,2] The materials involved are dispersive and thus the rotators and converters are generally narrow band. Moreover, the conventional rotators or converters are made of bulk materials, making it hard to be applied to miniaturized devices or lab-on-chip systems. For these reasons, polarization rotators or converters based on metamaterials,[3–6] metasurfaces,[7,8] perforated metal films,[9,10] and multi-layered metal antennas,[11,12] which have compact and planar structures and high performance, have been extensively investigated.

Among the polarization rotators and converters, cross-polarization converters which can convert the polarization of an incident linearly-polarized electromagnetic wave to its orthogonal direction have attracted tremendous attention.[13–23] Most cross-polarization converters are multi-layered structures consisting of three or more metal films with microstructures separated by dielectric spacers, where the near-field coupling between microstructures in neighboring metal films or interference of the multi-reflection waves supports the high-efficiency wide-bandwidth polarization conversion.[13–16] Comparably, the single-layered cross-polarization converters are of low efficiency and narrow band due to the lack of the near-field coupling and interference effect, which separate them from practical applications.[17–19]

Recently, several cross-polarization converters based on bi-layered metamaterials or perforated metal films have been studied.[20–23] The bi-layered converters, which are composed of two layer metal films with microstructures, are much easier to be fabricated in experiments than the multi-layered ones especially in the visible and infrared regions. Nevertheless, either the obtained conversion efficiency or the operating bandwidth is not satisfactory. For example, Li *et al.* proposed an L-shaped cavity-involved bi-layered polarization converter.[20] Cross-polarization conversion can be achieved at near infrared wavelength, but the efficiency of the outputting light is lower than 30%. Another polarization converter based on the double-layer metal hole array has also been presented.[21] The maximal transmission efficiency is as high as 90%. However, the working bandwidth is very narrow with the relative bandwidth smaller than 1%. Huang *et al.* investigated a bi-layered perforated metal film with rectangle holes in each film. The maximal conversion efficiency is above 52% and approaching 100% in the near infrared and microwave ranges, respectively. However, the full widths at half maxima (FWHMs) are only 80 nm (relative bandwidth ∼8%) and 570 MHz (relative bandwidth ∼15%) in the near infrared and microwave ranges, respectively.[22]

In this Letter, we study a bi-layered cross-polarization converter composed of two layer metal films perforated with rectangle hole pairs in each unit cell. The hole pairs in one metal film are perpendicular to the ones in the other metal film. Numerical calculations show that, in the infrared region, the maximal efficiency of the cross-polarization transmission light is higher than 74% with the FWHM approaching 291 nm and the relative bandwidth larger than 27%. In the microwave region, the maximal cross-polarization transmittance exceeds 95%, where the FWHM is larger than 1.4 GHz (the relative band-

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width ∼21%). The performance of the present bi-layered cross-polarization converter is superior to that of either the single-layered ones or other bi-layered ones.[17−23] In the end, an experiment has been conducted to verify our numerical calculations. The experimental results are in good accordance with the numerical calculations.

The proposed cross-polarization converter consists of two layers of metal films separated by a dielectric spacer with a hole pair array in each film. Figure 1(a) shows a unit cell of the structure. The hole pairs in the two metal films are perpendicular to each other (see Figs. 1(b) and 1(c)). If projected onto one plane, the corresponding holes in the two metal films overlap at the end of each rectangle holes, as seen in Fig. 1(d).

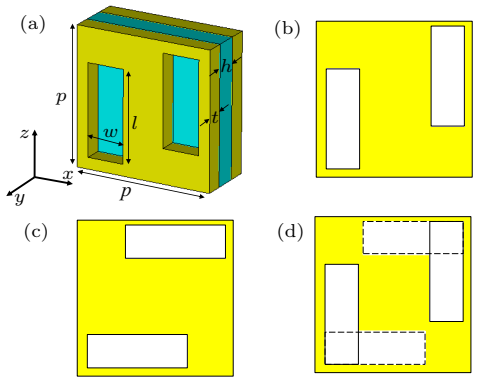


Fig. 1. (Color online) (a) Schematic view of the cross-polarization converter: double layer metal plates perforated with rectangle hole pairs separated by glass spacers. [(b), (c)] Rectangle hole pairs in the upper and lower metal films. (d) The hole pairs in the two-layer metal films projected on the same plane.

The transmission of the cross-polarization converter is numerically simulated with the finite-difference time-domain (FDTD) method-based commercial software FDTD Solutions 6.5 (Lumerical Solutions, Inc., Canada).[24] In the infrared regime, the two metal films, which are set as gold, are modeled by the Drude model $\varepsilon_{\rm m} = \varepsilon_\infty - \omega_{\rm p}^2/\omega(\omega + i\gamma)$, where $\varepsilon_\infty = 8$, plasma frequency $\omega_{\rm p} = 1.37 \times 10^{16}$ rad/s, and electron collision frequency $\gamma = 5 \times 10^{13}$ Hz.[25,26] The material of the spacer is glass with the refractive index $n_{\rm g} = 1.5$ and thickness $h = 90$ nm. The in-plane lattice periods of the converter are $p = 600$ nm in the x and y directions. The four rectangle holes in the two metal layers have the same length $l = 400$ nm and width $w = 160$ nm. The thicknesses of the two metal layers are $t = 50$ nm. The interested spectral range is in the near-infrared region with $\lambda \sim 700$–1500 nm.

In the simulations, the converter and the rectangle holes are assumed to be surrounded and filled with air ($n = 1$). The electromagnetic wave is incident normally (from the top side, in the $-y$ direction) upon the converter with the electric field polarized along the x axis. Probes with polarization in the x and y directions are set on the opposite sides of the structure to detect the transmitted electric field.

The simulated transmission spectra of the cross-polarization converter are shown in Fig. 2(a). Here $T_{xx} = |E_x|^2/|E_{x0}|^2$ and $T_{xy} = |E_y|^2/|E_{x0}|^2$ represent the transmittance along the x and y directions, respectively, E_x and E_y are the amplitudes of x- and y-polarized transmitted waves, respectively, and E_{x0} is the amplitude of the incident electromagnetic wave.

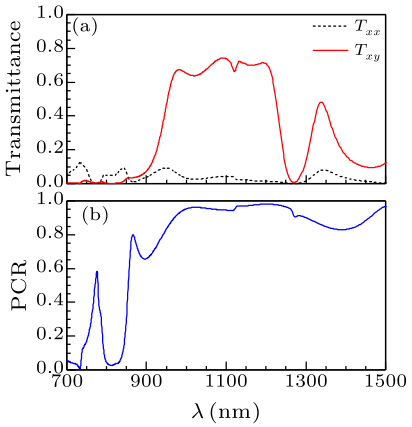


Fig. 2. (Color online) (a) The x- and y-polarization transmittance and (b) PCR of the cross-polarization converter versus wavelength. Here $p = 600$ nm, $l = 400$ nm, $w = 160$ nm, $h = 90$ nm, and $t = 50$ nm.

It can be seen from Fig. 2(a) that the co-polarized transmission is inefficient throughout the entire frequency band with efficiency T_{xx} mostly below 10%. Nonetheless, the maximal cross-polarized transmittance T_{xy} is higher than 74%. Moreover, between 952 and 1224 nm (more than 272 nm wide), transmittance T_{xy} is higher than 50%. The FWHM is 291 nm and the relative bandwidth is larger than 27%. Clearly, using the present bi-layered converter, a wide bandwidth and high efficiency cross-polarization conversion can be realized. The performance of the present bi-layered cross-polarization converter is superior to that of the single-layered and other bi-layered ones.[17−23]

This remarkable characteristic can also be demonstrated by the polarization conversion rate (PCR), which is defined as

$$\mathrm{PCR} = \frac{T_{xy}^2}{T_{xx}^2 + T_{xy}^2}. \tag{1}$$

It is clear that in the wavelength range from 952 to 1224 nm, over 80% of the energy of the transmitted light belongs to the cross-polarization component (see Fig. 2(b)). Particularly, between 1000 and 1250 nm, the cross-polarization light possesses over 90% transmitted energy.

The performance, e.g., the transmission efficiency and bandwidth, of the present cross-polarization converter based on the bi-layered hole pair array is superior to the one composed of the bi-layered single hole array.[22] The reason is partially due to the fact that the hole pair structure can allow more transmission of the electromagnetic waves than that of the single hole structure. To investigate other factors which result in high efficiency and wide bandwidth of

the cross-polarized conversion, numerical simulations of the electric-field and current distributions of the present structure will be carried out.

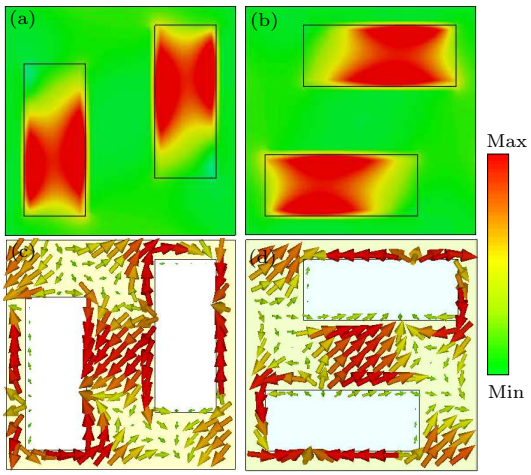


Fig. 3. (Color online) Electric-field [(a), (b)] and current distributions [(c), (d)] at half the thickness of the upper and lower metal plates at the wavelength of 1100 nm.

Figures 3(a) and 3(b) show the simulated electric-field distributions (in the x–y plane) at half the thickness of upper and lower metal films (at the wavelength $\lambda = 1100$ nm), respectively. It is seen that the electric fields are significantly boosted in the rectangle holes in the two metal layers, showing a standing-wave-like pattern. The electric-field in the holes in the upper metal film is along the x direction (E_y is very weak and not shown here), while the electric field in the holes in the lower metal film is along the y direction (E_x is weak instead), which shows the cross-polarization conversion.

The fundamental waveguide mode in the exit holes cannot be directly excited by the incident x-polarized light because the rectangle holes can only allow the transmission of light with polarization along the short hole edges.[27,28] The near-field interaction between hole pairs in neighboring metal films becomes responsible for the hole excitation and the polarization rotation.[22,23] To elucidate this point, we numerically simulate the current distributions at a wavelength of $\lambda = 1100$ nm and the results are shown in Figs. 3(c) and 3(d).

It can be found that, under the incident x-polarized light, oppositely circulating currents around the upper and lower hole ends of the inputting rectangle holes have been induced. The charges with opposite signs will accumulate on the central parts of the two long hole edges which behave as electric dipoles. Mediated by the near-field coupling, the currents and charges around the inputting holes will induce new currents and charges around the holes in the lower metal film due to the deep subwavelength thickness of the spacer.[15] The electric dipoles formed in the holes in the lower metal film emit far-field y-polarized radiation. Therefore, induced by the near-field coupling, a cross-polarization conversion can be realized using the bi-layered metal hole pairs.

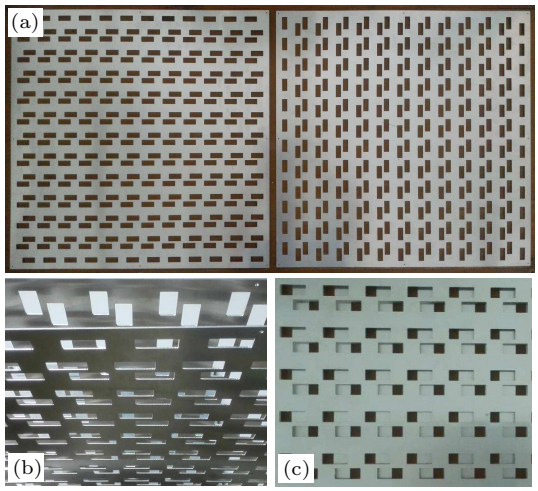


Fig. 4. (Color online) (a) Photographs of the two aluminum plates perforated with rectangle hole pairs. [(b), (c)] Side and top view of the cross-polarization converter.

In addition to the near-field coupling between orthogonal holes in neighboring metal films, there is also intra-hole coupling between two holes in the same metal film, i.e., the current surrounding one hole can flow to the other hole in the same film, as seen from Figs. 3(c) and 3(d). This short-circuit-like coupling behavior will suppress partly the accumulation of charges or electric dipoles around the hole, thus it is not beneficial for the transmission or cross-polarization conversion. Nonetheless, due to the doubling of hole area and near-field coupling between orthogonal holes, an overall improvement of transmission and cross-polarization conversion can be achieved.

The above effect, i.e., wide-band high-efficiency cross-polarization conversion of the bi-layer hole pairs, can also be realized in the microwave band. We investigate the effect experimentally and theoretically. In the experiment, rectangle hole pairs were cut into two freestanding aluminum plates using the water-jet cutting method. Here the thicknesses of the two-layer aluminum sheets are $t = 1$ mm. The rectangle holes in the two metal plates have the same length of $l = 24$ mm and the same width of $w = 10$ mm. The period of each unit cell is $p = 40$ mm. Figure 4 shows the photographs of the two perforated aluminum plates and the polarization converter. The distance between the two perforated aluminum plates is $h = 10$ mm.

In the measurement, the microwave was generated and detected by a pair of rectangle horn antennas. The incident electromagnetic wave with x-polarization impinged normally on the polarization converter. The x- and y-polarized transmittances were recorded by a vector network analyzer (AV3629A). Figure 5(a) shows the measured transmitted spectra of the polarization converter.

A numerical simulation is also carried out on the cross-polarization converter in the microwave regime. In the simulation, the dispersion of the aluminum

plates is described by $\varepsilon_{\rm m} = 1 + i\sigma/\omega\varepsilon_0$, where the electrical conductivity $\sigma = 3.5 \times 10^7$S/m. The simulated results are also shown in Fig. 5(a). Overall, the experimental observation agrees well with the numerical results despite fabrication error and random error in measurement. The simulated PCR is shown in Fig. 5(b).

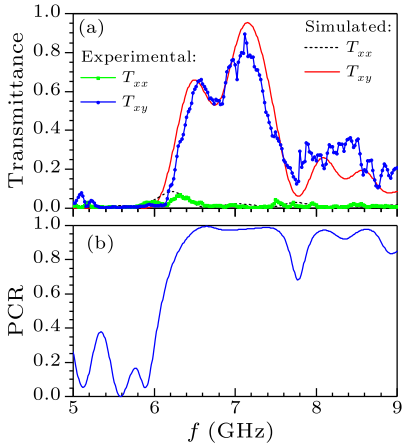


Fig. 5. (Color online) (a) Experimental (lines with symbols) and simulated (lines without symbols) transmittance, and (b) simulated PCR of the cross-polarization converter versus wavelength. Here $p = 40$ mm, $h = 10$ mm, $t = 1$ mm, $l = 24$ mm, and $w = 10$ mm.

Comparing Fig. 2(a) with Fig. 5(a), one can find that, for the same metal metasurface-based polarization rotator, the transmittance at the optical frequencies is much lower than that at the microwave frequencies. The same conclusion can also be found in the literature.[10,15,22] The reason is that, in the microwave region, the metal can be viewed as a perfect electric conductor due to the low material loss, while in the optical frequency region, the loss is much larger than that in the microwave frequency region, which results in more energy losses at the optical frequencies than at the microwave ones.

Similar to the results in the near-infrared regime, here T_{xx} is still negligible (lower than 10%) in the interested microwave region from 5 to 9 GHz, while T_{xy} remains as a wide bandwidth and high transmissivity (see Fig. 5(a)). From 6.3 to 7.5 THz, about 1.3-GHz wide, the efficiency T_{xy} is above 50%. Especially, at the frequency of 7.1 GHz the efficiency is higher than 95%. In the microwave regime, the FWHM is larger than 1.4 GHz and the relative bandwidth ∼21%. The PCR is mostly higher than 80% in the frequency range from 6.2 to 9 GHz (see Fig. 5(b)). Clearly, in the microwave region, the performance of the present bi-layered cross-polarization converter is also superior to that of the single-layered and other bi-layered ones.[17–23]

It can be found from Fig. 5(a) that there are two dominant transmission peaks. The underlying mechanism of the two peaks can be summarized as follows:[15] in the near-field coupling regime, the waveguide modes in the upper and lower rectangle holes are coupled strongly. The left peak in Fig. 5(a) stems from the anti-symmetric coupling modes of the system, while the right peak originates from the symmetric coupling modes (for details please see Ref. [15]).

In conclusion, we have proposed a cross-polarization converter composed of bi-layer metal films perforated with rectangle hole pairs. The structure can rotate the polarization of incident light by 90° with high transmission efficiency and wide bandwidth in the infrared or microwave frequency bands. The effect is associated with the near-field coupling between holes in neighboring metal films. The experiment in the microwave regime verifies the numerical simulations.

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