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A reflecting-type highly efficient terahertz cross-polarization converter based on metamaterials

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We propose and experimentally demonstrate a wideband linear polarization converter in a reflection mode operating from 2.4 to 4.2 THz with conversion efficiency of more than 80%. Our device can expand the applications to a higher frequency band. A numerical simulation is performed for this metamaterial converter, which shows a good agreement with experimental results. Importantly, a concise and intuitive calculating model is proposed for the Fabry–Pérot cavity. The theoretical results indicate that the underlying reason for the enhanced polarization conversion is the additional phase difference induced by the resonance of the meta-structure and multiple reflections within the Fabry–Pérot cavity.

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Polarization of light is one of the basic properties that has been studied in various fields and applications, such as transformation optics, anomalous refraction4, optical spin Hall effect23, sub-wavelength focusing4, and laser beam shaping2. Control and manipulation of light polarization states plays a fundamental role in these fields. A polarization converter can convert polarization states into another desired one with high efficiency via simple experimental configurations. Recently, metamaterials have enabled high-efficiency and broadband polarization converting, showing outstanding potential for further applications and expanding the studies of metamaterials1,2,6. Conventional polarization converters use the birefringence effects of crystals. However, these converters show obvious drawbacks, that is, bulky configuration and narrow band.

Various terahertz (THz) metasurface devices have been specifically proposed either for cross-polarization converting or linear-to-circular polarization converting4,12,24. Most of them are three-layered sandwich structures working in the reflection mode or transmission mode. They consist of a polyimide dielectric spacer, a grating ground, and a layer of periodic cells, such as V-shaped antennas, C-shaped antennas, or split-ring resonators4,12,18. However, almost all these designs aimed at applications in the range of frequencies from 0.5 to 1.4 THz22,23. This lower band of the THz region has very limited applications in polarization imaging26–28, THz spectroscopy29, THz quantum cascade laser systems31, and THz photonics32 due to its wave-like characteristics.

In this Letter, we demonstrate numerically and experimentally a metamaterial reflective polarization converter that operates with high efficiency (>80%) in the frequency band from 2.4 to 4.2 THz. Furthermore, we propose an intuitive and simple model to account for the polarization converting effect. Generally, there are two explanations for the process of polarization conversion. One is the magnetic resonances between the meta-structure layer and bottom layer, which are both metallic and form a sandwich structure together with the central insulating layer, and it can be revealed qualitatively from simulation results of the surface current loop2. The other one is the Fabry–Pérot (F-P) cavity model related to the propagating and truncation of the confined mode between two metallic layers, which is widely accepted by many researchers1,15. However, it is intricate in calculation and fails to expose the role of the metasurface layer explicitly. Our method indicates that the meta-structures have different and independent effects on two orthogonal directions, and thus they can be dealt with separately. In the following part, we explain the polarization converting process in the u−v coordinate system, and we can see that the physics is very clear; that is, electric resonance and the F-P cavity together result in a 180° phase difference between the u-polarized and v-polarized components. We expect that our demonstration will expand applications of metamaterials in the THz region and simplify the design and analysis process of metamaterial-based devices.

The schematic diagram of our proposed linear polarization converter is illustrated in Fig. 1(a). The converter is composed of three layers, which are cut-wire arrays, a dielectric spacer, and a ground plane acting as a mirror. The specific parameters of a unit cell are shown in Fig. 1(c), which are optimized by multiple simulations. The device was fabricated on the polyimide film by UV lithography and the lift-off process, and the microscopic image of the sample is shown in Fig. 1(b).
Between 2.4 and 4.2 THz, the reflectance $E_1(d)$. In order to evaluate the performance of our device with a small angle (less than 10°) deviated from the $x$-axis, we present an explicit method to account for the polarization converting effect with experimental and numerical evidences. The beat wave is used to verify the physical image. Here, we present an explicit method to account for the polarization converting effect with experimental and numerical evidences.

The finite-difference time-domain (FDTD) method is adopted to simulate the behavior of the device. The periodic boundary condition is applied in the $x$ and $y$ directions. The incident angle $\theta_i = 10^\circ$, and electric field $E_0$ is linearly polarized in the $x$ direction. All the dimensions are shown, $A_x = A_y = 40 \mu$m, $t_1 = 15 \mu$m, $L = 38 \mu$m, and $W = 3 \mu$m. The periodic meta-structure units and bottom mirror are made of gold via electron beam evaporation. The dielectric spacer is polyimide film with $\varepsilon = 3.5(1 + 0.05i)$. (d) Experimentally measured and numerically simulated co-polarized and cross-polarized reflectance, corresponding to the $x$ and $y$ directions in our experiment, respectively.

The incident angle has little influence on the performance of our converter when it is less than 20°. One is magnetic resonance between meta-structure layers and bottom layer, due to current loops consisting of a resonance current in metasurface and an induced current in the ground mirror, and it is well proved qualitively that magnetic resonance leads to an enhancement of the polarization converting effect. The other one is the F-P cavity model demonstrated in Refs. [1,23]. But, both are presented in a complex way and fail to give a clear physical image. Here, we present an explicit method to account for the polarization converting effect with experimental and numerical evidences.

First of all, we consider all the polarization components and physical effects in the $u-v$ coordinate system that rotates about the $z$ axis 45° from the $x-y$ coordinate and the reflected light. As shown in Fig. 1(c), the direction of meta-structures is 45° with the $x$ axis. Then, a analyzer is utilized for measuring the $x$ and $y$ components of the reflected light. The polarizer and analyzer can be added into the FTIRS as additional accessories, as shown in Fig. 1(a). First of all, an Au-coated mirror, which is assumed to be a perfect reflector, is placed at the position of the converter. The $x$ and $y$ components of the reflected light are measured. Then, the converter is placed at the same position with identical experimental setups, and the reflected lights are obtained in the same way. The reflection amplitudes are the ratios of the two results, that is, the ratios of the latter results to the former results.

The experimental and simulated results are shown in Fig. 1(d). In order to evaluate the performance of our designed converter, we define reflectance of any polarization component as

$$R_{mn} = \frac{I_{r,m}}{I_{i,n}} = \frac{E_{r,m}^2}{E_{i,m}^2} = r_{mn}^2. \quad (2)$$

The subscripts $m$ and $n$ indicate the polarization states of electromagnetic (EM) waves, while $i$ denotes incident EM waves, and $r$ denotes reflected EM waves. For instance, $I_{r, n}$ denotes the intensity of $m$-polarized reflected EM waves. Then, we can define the polarization converting efficiency (PCE) as $\text{PCE} = R_{yx}$ when incident light is $x$-polarized, as in our experimental setup. The experimental results of reflectance are presented in Fig. 1(d). Between 2.4 and 4.2 THz, the reflectance $R_{yx}$ or PCE is more than 80%, which means the cross-polarization light carries 80% of the incident energy, and this is much higher than for other converters. The experimental results fit well with the simulation results, as shown in Fig. 1(d). Although the simulated results show a little wider operating band and a higher PCE, it is reasonable due to fabrication and measurements deviation. There is significant energy absorption at around 4.5 THz due to the resonance of the metastructure. For verification, we experimentally excluded the possibility of dielectric absorption.

Generally, there are two mechanisms demonstrated previously to account for the polarization converting effect. One is magnetic resonance between meta-structure layer and bottom layer, due to current loops consisting of a resonance current in metasurface and an induced current in the ground mirror, and it is well proved qualitatively that magnetic resonance leads to an enhancement of the polarization converting effect. The other is the F-P cavity model demonstrated in Refs. [1,23]. But, both are presented in a complex way and fail to give a clear physical image. Here, we present an explicit method to account for the polarization converting effect with experimental and numerical evidences.

First of all, we consider all the polarization components and physical effects in the $u-v$ coordinate system that rotates about the $z$ axis 45° from the $x-y$ coordinate.
The theoretical results corresponding to the phases. We can find in Fig. 2(a) that exp (f). The theoretical results of magnitudes of re and trans are in agreement with the experimental and simulated results, which indicates that our proposed calculating method 

\[
tvu = ruu = rvu = 0 \text{ in the considered frequency region. (c) The phase } \phi^f_{vu}, \text{ which mainly contributes to polarization conversion. The other phases are zeros. (d) The schematic diagram of the F-P-like cavity model for multiple reflections. (e) Theoretical phases with } v \text{ and } u \text{ components, which are shown in reflection mode results from the equality of magnitudes of } u \text{ and } v \text{ components. (f) Theoretical reflection and transmission amplitudes of cross-polarization and co-polarization.}
\]

Then, we obtain total v- and u-component reflection by adding multiple reflections. The results are geometric series. The v-component of the total reflected field can be calculated as

\[
E'_v = E_i \exp(jkz) \times \left\{ r_{vu} + t_{vu}^2 \exp(i \times 2\phi^f_{vu}) \exp(i \times 2kt_v) + r_{vv} \exp(i \times 4kt_v) + r_{vv}^2 \exp(i \times 6kt_v) + \cdots + r_{vv}^{n-1} \exp(i \times 2nkt_v) + \cdots \right\} e_v.
\]

The sum can be obtained when } n \to \infty,
\[
E'_v = E_i \exp(jkz) \left[ r_{vu} + t_{vu}^2 \exp(i \times 2\phi^f_{vu}) \exp(i \times 2kt_v) \right] \frac{1}{1 - r_{vu} \exp(i \times 2kt_v)} e_v.
\]

Similarly, the u component can be obtained, noting that } \phi^f_{vu} \text{ vanishes:
\[
E'_u = E_i \exp(jkz) \left[ r_{uu} + t_{uu}^2 \exp(i \times 2\phi^f_{uu}) \frac{\exp(i \times 2kt_u)}{1 - r_{uu} \exp(i \times 2kt_u)} \right] e_u.
\]

The reflection and transmission coefficients } r_{uu}, t_{uu}, r_{vv}, \text{ and } t_{uu} \text{ in the above functions have been acquired from simulation results of a single metasurface layer (the cut-wire layer).

Finally, we obtained the results that the } v \text{ and } u \text{ components have a nearly } 180^\circ \text{ phase difference within } 2.4-4.2 \text{ THz, as shown in Fig. 2(e) on the blue line, but the magnitudes are the same and are not represented due to the mirror reflecting almost } 100\%. \text{ Thus, the } v \text{ and } u \text{ components can be combined into a linearly polarized light whose direction is } 45^\circ \text{ to the } u \text{ axis. If we present it in the } x-y \text{ coordinates, the cross-polarization (y-polarization) and co-polarization (x-polarization) reflectance can be obtained, as shown in Fig. 2(f). The theoretical results are in agreement with the experimental and simulated results, which indicates that our proposed calculating method is workable, and the F-P-like cavity model plays a main role in the polarization converting process.

In conclusion, we demonstrate a high-efficiency and wideband polarization converter in the reflection mode to convert an } x \text{-polarized THz wave to a } y \text{-polarized wave. The operating range of frequency is from } 2.4 \text{ to } 4.2 \text{ THz, and the cross-polarized THz wave carries more than } 80\% \text{ of the incident energy. We expect applications in THz photonics, where previously demonstrated converters operating in the frequency range from } 0.6 \text{ to } 1.4 \text{ THz cannot be applied. Furthermore, we proposed a more intuitive and essential method based on the F-P-like cavity model to account for this linear polarization converter. Thus, the essence of the polarization converting process can highlight that the transmission phase of the } v \text{-polarized component and multiple reflections in the F-P-like cavity play fundamental roles. The inconformity of our theoretical
results may be caused by the magnetic resonance mentioned in some articles, but it does not have a significant contribution.

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