Manipulating light polarizations with a hyperbolic metamaterial waveguide

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In this Letter we demonstrate that a hyperbolic metamaterial (HMM) waveguide array exhibits a giant modal birefringence between the TE and TM modes by utilization of a rectangular waveguide cross section. We further reveal that the designed polarization manipulation device using such a HMM waveguide array with a subwavelength thickness presents the ability to function as a polarizer or quarter- or half-wave plate that enables transmission only for electromagnetic wave (EW) that is polarized at a specific direction, or converting linearly polarized EW to circularly and elliptically polarized EW or rotating linearly polarized EW with 90° at terahertz (THz) frequencies. A giant modal birefringence between the TE and TM modes from 0.8 to 2 between 2 and 4.8 THz is achievable, which is dozens of times higher than conventional quartz birefringent crystals for THz waves. This polarization manipulation device has the performance merits including high transmission efficiency, ultra-compactness, and tunable birefringence, offering a promising approach to manipulating the polarization states of EW.

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Efficiently and fully controlling of the polarization state of an electromagnetic wave (EW) is of central importance for the progress of physics, chemistry, biology, and optics [1]. Conventionally, various architectures have been proposed and demonstrated to be capable of manipulating light polarization states, such as birefringent crystals, liquid crystals, Kerr and Faraday effects, and Brewster angle effects [1]. However, the polarization manipulation devices based on these methods typically require a system with a large thickness (normally dozens of wavelengths), which is inconvenient in low-frequency applications. Especially, the most natural materials exhibit weak response to terahertz (THz) waves, inducing that the development of THz polarization manipulation devices is far inferior to its counterpart in the optical/infrared domain despite the fact that manipulation of light polarization is crucial in THz fields [2].

Alternatively, plasmonics and metamaterials have provided an unprecedented approach to control the polarization states of EW at subwavelength scale over the whole spectral region from microwave to visible frequencies [3–6]. However, it is very challenging to build an ideal polarization converter based on resonant metamaterials due to the existence of the birefringent effects that are usually accompanied by circular dichroism [3]. In addition, most of these polarization converters suffer from low intensity transmission owing to the intrinsic resonance nature [4]. Quite recently, it has been theoretically demonstrated that at terahertz frequencies, inducing that the development of THz polarization manipulation devices is far inferior to its counterpart in the optical/infrared domain despite the...
cross section, different polarization states of EW have different transmission property, leading to a modal birefringence between the TM and TE modes. Figure 1(a) schematically shows the proposed polarization manipulation device using subwavelength metal/dielectric multilayer based HMM waveguide array with a rectangular waveguide cross section. Each unit cell is comprised of a HMM waveguide on a dielectric substrate [Fig. 1(b)]. Here, the TM (TE) mode of the HMM waveguide array is defined as the electric field polarizing along the x(y) direction. For such a periodical optical structure, the dispersion curve can be accurately retrieved by the well-known Bloch mode method [11]. In our work, we have employed a commercial finite difference time domain (FDTD) solver to perform Bloch mode calculation of dispersion curves of the HMM waveguide array [12]. The presented HMM waveguide array is seen as a three-dimensional photonic crystal with the lattice constants of Px, Py, and Pz along x, y, and z directions. For retrieving the real part of the propagation constant of the HMM waveguide array, we scan over the propagation constant along the z direction, Kz, from 0 to π/Pz in Bloch mode calculation. By handling the electric field of the TE and TM modes that is collected by a monitor, the real part of the propagation constant for the TE and TM modes along z direction can be numerically extracted, respectively. It is observed from Fig. 2 that the real part of the propagation constant of the TE (TM) modes can be significantly influenced by the HMM width along the polarization direction of light, Wx(Wy). Especially, the cut-off frequency of the TE (TM) modes is strongly dependent on Wy(Wx). It is apparent that, for a fixed width of the HMM waveguide, the maximum modal birefringence occurs as light frequency approaches the cut-off frequency of the TM (TE) mode. For example, with Wx = 9, and Wy = 3 µm both the TM and TE modes can be supported if light frequency is below 4.8 THz, corresponding to the cut-off frequency of the TM mode. However, the real parts of their propagation constants are quite different below 4.8 THz, clearly indicating the existence of giant modal birefringence.

Figure 3(a) clearly shows that the modal birefringence, Δn, increases monotonously with light frequency, and reaches the maximum value at 4.8 THz. The birefringent index, Δn, between the TM and TE modes is from 0.8 to 2 between 2 and 4.8 THz. In contrast, the birefringent index, Δn, of conventional quartz crystals for THz waves is only about 0.048 [15], which is dozens of times smaller than that of the present HMM waveguide array. The phase difference of the transmitted light between the TM and TE modes can be written as

\[ Δφ = (Kz1 − Kz2)H, \]

where Kz1 and Kz2 denote the propagating constants of the TM and TE modes along the z direction, respectively. It should be noted that with a fixed H, a larger value of Δφ can be obtained if light frequency approaches the cut-off frequency of the TM mode. However, the propagation loss is significantly increased as light frequency approaches the cut-off frequency of the TM mode [Fig. 3(b)], which can be attributed to the fact that slow-light occurs, and hence largely enhances light

**Fig. 1.** (a) Schematic of the polarization manipulation device comprised of a rectangular HMM waveguide array on a dielectric substrate, whose unit cell is shown in (b). The polarization angle, β, is defined as the angle between the polarization direction and +x direction. The width of the HMM waveguide, and lattice constant along x(y) direction are denoted as Wx(Wy), and Px(Py), respectively. The thickness of metal and dielectric layers is represented by tm and td, respectively. The lattice constant along z direction is denoted as Pz (= tm + td), and the height of the HMM waveguide array is represented by H.

**Fig. 2.** (a) and (b) The dispersion relations of the TM and TE modes for different values of Wy as Wx is fixed at 9 µm. (c) and (d) The dispersion relations of the TM and TE modes for different values of Wx as Wy is fixed at 3 µm. In the calculation, the structural parameters are set to be Px = 11 µm, Py = 8 µm, and Pz = 0.34 µm (tm = 0.14 µm, td = 0.2 µm). Al and GaAs are selected as the metal and dielectric layers. The relative permittivity of Al layer is described by well-known Drude model, ε(ω) = 1 - ωp^2/ω(ω - iωτ) where ωp = 3570 THz, and ωτ = 19.4 THz are extracted by fitting the experimental data [13]. The permittivity of GaAs layer is set to be 12.96 [14].

**Fig. 3.** Dependence of the real part (a) and imaginary part (b) of the effective refractive index for the TM and TE modes with Wx = 9 µm, Wy = 3 µm on light frequency. k0 is the wavenumber in air. The modal birefringence between the TM and TE modes, Δn, versus light frequency is indicated in (a). The imaginary part of the propagation constant in (b) is numerically retrieved by using the Numerical FDTD solution mode solver [16].
absorption near the cut-off frequency [8]. Consequently, to balance the propagation loss and the height of the polarization manipulation device, the operating frequency used for polarization manipulation should be properly selected.

Considering the practical situation, it is assumed that the HMM waveguide array is placed on the top of a loss-free Poly tetrafluoroethylene (PTFE) substrate, which is typically used in THz field. The phase difference, \( \Delta \phi \), versus light frequency with four different heights of 18.7, 22.1, 25.5, and 28.9 \( \mu m \), respectively, corresponding to 55, 65, 75, and 85 pairs of AlGaAs layers, respectively. In the calculation, a loss-free poly tetrafluoroethylene (PTFE) substrate for the HMM waveguide is involved in FDTD simulation for retrieving the phase difference. The relative permittivity of PTFE is 1.9 at THz frequencies [17].

Fig. 4. Phase difference, \( \Delta \phi \), extracted from FDTD simulation (solid lines) and the dispersion relation (dashed lines) with four different heights of 18.7, 22.1, 25.5, and 28.9 \( \mu m \). In the calculation, a loss-free poly tetrafluoroethylene (PTFE) substrate for the HMM waveguide is involved in FDTD simulation for retrieving the phase difference. The relative permittivity of PTFE is 1.9 at THz frequencies [17].

Fig. 5. Amplitude ratio (a), (d), ellipticity (b), (e), and intensity transmission (c), (f) versus the polarization angle \( \beta \) at 3.6 (a)–(c), and 4.7 (d)–(f) THz, respectively. The sketch map of the polarization states of incident and transmitted light with different incident polarization angles is given in the insets of (b) and (e). The height of the HMM waveguide is 18.7 \( \mu m \).
behaves like a quarter- or half-wave plate that enables linear-circular polarization conversion [Fig. 6(c)] or 90° polarization rotation [Fig. 6(d)]. It is worth emphasizing here, for both cases the height of the HMM polarization converter can be effectively reduced as light frequency approaches the cut-off frequency (4.8 THz) of the TM mode, but which is at the cost of the increased transmission loss. We are able to achieve a much higher conversion efficiency at a much lower frequency by using an even higher HMM waveguide array, especially for the case of 90° polarization rotation [Fig. 6(d)]. The intensity transmission for 90° polarization rotation can be greatly increased from 0.42 with $H_{0.136}$ to 0.62 with $H_{0.34}$ [shown in Fig. 5(f)] to 0.62 with $H_{0.34}$ [Fig. 6(d)].

It should be noted that, to build an ideal polarization rotator based on resonant metamaterials is a very challenging issue because of the inevitable birefringent effects that are usually accompanied by circular dichroism [3]. The present HMM polarization converter, originating from the large modal birefringence of the HMM waveguide array between the TM and TE modes, is capable of working as an ideal polarization rotator that the polarization states of transmitted light can be precisely controlled by adjusting structural parameters of the HMM waveguide array and the polarization angle of incident EW. The conversion efficiency of the polarization converter here is comparable to or even higher than that of metamaterial-based polarization converters in the THz domain previously reported [19]. For the experimental fabrication of the presented HMM waveguide array, we can first employ deposition techniques (e.g., sputtering and/or E-bean evaporation) to form the alternating metal/dielectric multilayer on the PTFE substrate. Then, a focused-ion-beam milling is followed to pattern the HMM waveguide array.

In conclusion, we have demonstrated that a HMM waveguide array with a rectangular cross section presents a giant modal birefringence, which is dozens of times higher than conventional quartz birefringent crystals for THz waves. We further reveal that the designed HMM polarization manipulation device presents the ability to function as a broadband THz polarizer that allows for transmission of EW that is only polarized at a specific direction with an ultra-high extinction ratio and low insertion loss. Additionally, the presented HMM waveguide array can behave like a conventional quarter- or half-wave plate that shows the capability to convert linearly polarized EW to circularly and elliptically polarized EW, or rotate linearly polarized EW with high conversion efficiency. Our results offer a novel and feasible approach to develop a practical polarizer, or quarter- or half-wave plate, which will impact a broad range of applications at THz frequencies. We emphasize that our proposal is scalable and can be applied at other frequencies as well.

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**REFERENCES AND NOTE**

12. The Bloch mode calculations were carried out with Bandsofte software from Rsoft Design Group, http://www.rsoftdesign.com.