Manipulate light polarizations by metamaterials: from microwave to visible

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Abstract

In this paper, we review our recent efforts in employing anisotropic metamaterials to manipulate electromagnetic wave polarizations, including conversions between different polarization states and rotations of polarization direction, in frequency domains ranging from microwave to visible. We first present a general theoretical analysis on the problem, and then discuss our experimental efforts in fabricating metamaterial samples and realizing the predicted polarization manipulation effects, in both reflection and transmission geometries.

1. Introduction

Polarization is an important characteristic of electromagnetic (EM) waves. It is always desirable to have full control of the polarization states of EM waves. Conventional methods to manipulate polarization include using optical gratings, dichroic crystals, or employing the Brewster and birefringence effects, etc.. Such systems are typically much thicker than wavelength and suffer the energy loss issue since they are not perfectly transparent or reflective.

Metamaterials (MTM), with arbitrary values of effective ε and μ, offer us new opportunities to manipulate EM wave polarizations. In a series of recent works [1-5], we designed and fabricated appropriate anisotropic MTMs in microwave and visible frequency regimes, and performed experiments to demonstrate several fascinating polarization manipulation effects, including the polarization conversions and rotations, and so on. These proposed devices are typically much thinner than wavelength with high efficiency of polarization manipulation. In what follows, we briefly review these efforts.

2. Theoretical analysis

Consider the reflection geometry first. Suppose an incident light, polarized such that $\vec{E}^{in} = \left(E_x\hat{x} + E_y\hat{y}\right)$, strikes on the top surface of an anisotropic MTM with anisotropic $\vec{\varepsilon}, \vec{\mu}$ tensors. The reflected light is generally $\vec{E}^r = \left(r_x E_x\hat{x} + r_y E_y\hat{y}\right)$ with $r_x = (Z_x - 1)/(Z_x + 1)$ and $r_y = (Z_y - 1)/(Z_y + 1)$, where $Z_x = \sqrt{\mu_y}\big/\sqrt{\varepsilon_x}$ and $Z_y = \sqrt{\mu_x}\big/\sqrt{\varepsilon_y}$ are the impedance for two incident polarizations. Then, if we have

$$Z_x \cdot Z_y = 1 \qquad (1)$$

so that $r_x = -r_y$, the reflected light takes a polarization $\vec{E}^r \sim \left(E_x\hat{x} - E_y\hat{y}\right)$, which is different from the incident polarization. In particular, in the case of $E_x = E_y$, the polarization vector of reflected light is perpendicular to that of the incident light.

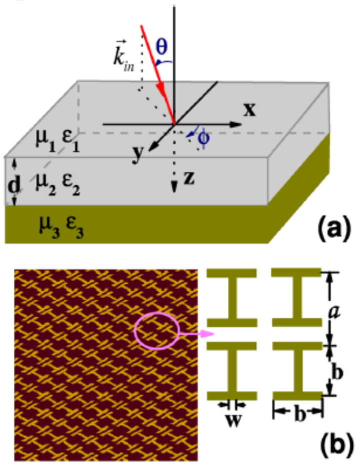
We next consider the transmission geometry. Assuming the same incident light, the transmitted wave through a slab of anisotropic MTM is then $\vec{E}^t \sim \left(t_x E_x\hat{x} + t_y E_y\hat{y}\right)$, where $t_x = T_x e^{i\varphi_x}, t_y = T_y e^{i\varphi_y}$ are the transmission coefficients. If we have

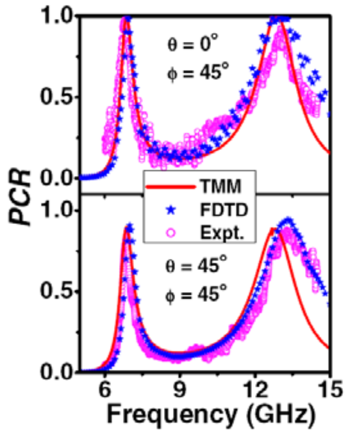
$$T_x = T_y = 1,\ \varphi_y - \varphi_x = \Delta\varphi \gg 1\ , \qquad (2)$$

the MTM would behave as a transparent phase plate for EM wave, and thus the polarization of transmitted wave can be freely and efficiently manipulated.

3. Realizations

We present three explicit examples in this section. The model system we proposed in microwave regime is shown in Fig. (1a), which consists of an anisotropic magnetic MTM (with $\mu_{xx} = 1 + 70/12.71^2 - f^2$, $\mu_{yy} = 1 + 22/6.80^2 - f^2$) put on top of a perfect electric conductor (PEC). A picture of a fabricated MTM sample is shown in Fig. 1(b). At most frequencies, the top magnetic MTM layer is transparent and light can directly "see" the PEC on the back, indicating the entire system possesses low impedance. However, at the resonances where $\mu_{xx}(\mu_{yy}) \to \pm\infty$, light is reflected directly by the top MTM layer, indicating that the entire system behaves like a perfect magnetic conductor (PMC). Therefore, at the resonance frequency $f = 6.80$ GHz, we have $Z_x \to \infty, Z_y \to 0$ and thus $Z_x \cdot Z_y \to 1$. The same is true for another resonance $f = 12.71$ GHz. Therefore, the designed system makes Eq. (1) satisfied at two frequency intervals. Microwave experiments were performed to demonstrate several polarization-manipulation effects [1], including the (*s* to *p*) polarization conversion as shown in Fig. 2.





(Left) Fig.1 (a) Configuration of the model system. (b) Picture of the fabricated MTM. (Right) Fig. 2 Measured and calculated spectra of polarization conversion ratio (PCR) for normal and off-normal incidences.

At optical frequencies, we cannot achieve a PEC or a PMC. However, we can still design appropriate MTMs to satisfy Eq. (1) at some frequencies. Our designed system is schematically shown in Fig. 3(a), while an SEM picture of a fabricated sample is shown in Fig. 3(b). We obtained the effective $\vec{\varepsilon}$ and $\vec{\mu}$ of the MTM using the retrieval method, and found that Eq. (1) can be approximately satisfied at two wavelengths 628 nm and 766 nm, thanks to the fact that both electric and magnetic resonances co-exist in such an optical MTM. Experiments confirmed that the (*s* to *p*) polarization conversion ratio is maximized at those two wavelengths [3].

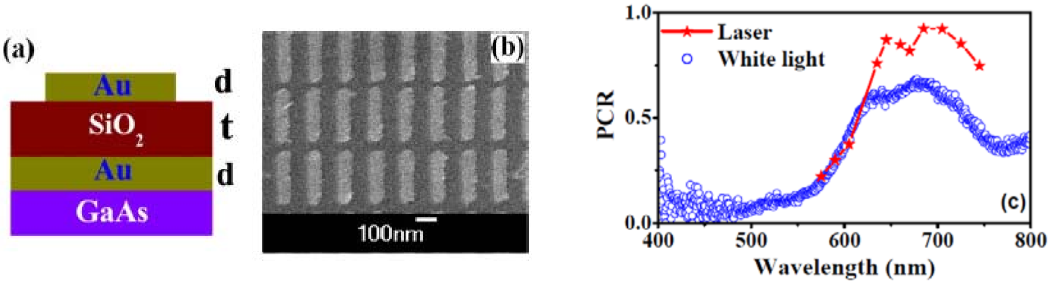
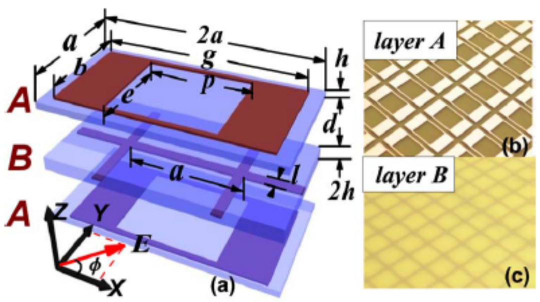
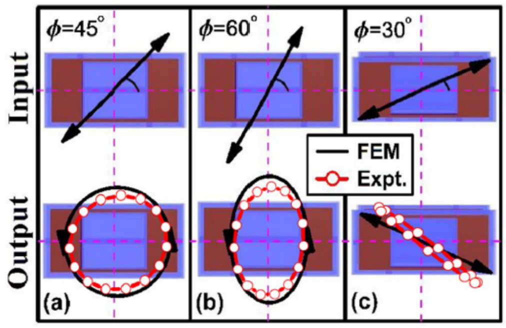


Fig. 3 (a) Side-view geometry of the system. (b) SEM picture of the sample. (c) PCR spectrum measured by Laser or white-light sources.

Recently, we succeeded in designing an MTM to satisfy Eq. (2), which can be employed to manipulate EM polarizations in transmission geometry [5]. Although several other MTM-based devices were already proposed to realize similar effects, a unique character of our design is that it is *perfectly transparent* for EM waves at the working frequency, and thus the efficiency of the device is 100% theoretically. As shown in Fig. 4, our system is a laterally *anisotropic* ABA structure consisting of three MTM layers, in which layer A is an electric MTM and layer B is a metallic mesh. We found a series of *perfect* transparency bands for two incident polarizations (i.e., $\vec{E} \parallel \hat{x}$, $\vec{E} \parallel \hat{y}$), governed by either the effective-medium-theory (EMT) or the extraordinary optical transmission (EOT) mechanisms. The key idea of our design is to adjust (through structural optimization) the *perfect* transmissions for two incident polarizations, one governed by the EMT mechanism and another by EOT mechanism, to occur at the same frequency. Since the transparencies for two incident polarizations are different, the associated phase change $\Delta\varphi = \varphi_y - \varphi_x$ can be quite large. Indeed, we found by both simulations and experiments that Eq. (2) can be satisfied at $f = 5.1\text{GHz}$ for the present design, with $\Delta\varphi \approx 90^\circ$. Such a big phase difference is remarkable since our system is only $\lambda / 20$ thick. Microwave experiments demonstrated several fascinating polarization-manipulation effects, including the linear-to-circular and linear-to-elliptical polarization conversions, and the giant rotation of the polarization direction (Fig. 5).





(Left) Fig. 4. Geometry of the device and sample pictures. (Right) Fig. 5. Polarization manipulation effects realized by our device.

4. Conclusions

In summary, we reviewed our recent efforts in using anisotropic MTMs to efficiently control the polarization properties of EM waves, in both reflection and transmission geometries. We present three explicit examples, in frequency domain ranging from microwave to visible, to illustrate the polarization manipulation effects, including the polarization conversions and rotations. Experimental results are in excellent agreement with theoretical calculations. Many applications of our findings are being expected.

References

[1] Jiaming Hao, *et al*., **Phys. Rev. Lett**. **99,** 063908 (2007)..
[2] Jiaming Hao and L. Zhou, **Phys. Rev. B 77**, 094201 (2008)
[3] Jiaming Hao, *et. al*., **Phys. Rev. A**. **80,** 023807 (2009).
[4] Jiaming Hao, M. Qiu and L. Zhou, **Front. Phys. China 5**, 291 (2010).
[5] Wujiong Sun, Qiong He, Jiaming Hao, Lei Zhou, **Opt. Lett**. **36,** 927 (2011).

