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# Nonreciprocal transmission of electromagnetic waves by three-layer magneto-optical mediums

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We investigate the non-reciprocal transmission properties of a three-layer structure filled with magneto–optical medium and normal medium. Based on the transfer matrix method, we deduce the total transmission coefficient for a one-dimensional (1D) structure with anisotropic mediums. When two-side layers with magneto–optical medium loaded in opposite external magnetic field, the time-reversal symmetry of transmission properties will be broken. Our numerical results show that the non-reciprocal transmission properties are influenced by external magnetic fields, incident angle, and thickness of the normal medium layer. Since the non-reciprocal properties can be easily realized and adjusted by the simple structure, such a design has potential applications in integrated circulators and isolators.

**Keywords:** magneto–optical medium, nonreciprocal transmission, nonreciprocity

**PACS:** 41.20.Jb, 73.20.Mf, 73.90.+f **DOI:** 10.1088/1674-1056/28/2/024101

## 1. Introduction

The phenomena of magneto–optic effect (MOE) discovered by Faraday in the middle of the 19th century,[1] which triggered a flood of research on fundamental physics and applications due to its special properties,[2–7] such as the Faraday effect, Cotton Mouton effect, and magneto–optical Kerr effect. Because the electromagnetic (EM) parameters of magneto–optical mediums are anisotropic and asymmetric, and also can be modulated by the external magnetic field, one of the other novel properties in the magneto–optical mediums (MOMs) is nonreciprocity.[8–13] In other words, the wave propagation in the MOMs breaks the time-reversal symmetry. Because of its important applications in integrated circulators and isolators, the nonreciprocal properties of MOMs have attracted considerable attention.

However, the weakness of MOE leads to the obstacles of magneto–optical effects in practical applications. Therefore, it is essential to sweep the obstacles to seek for the strategy to enhance MOE. Surface electromagnetic waves, which exist at the interfaces separating different media, are proven to be important approaches in enhancing the MOE. One of the most well-known types of these waves is optical Tamm states (OTSs) which have existed in a photonic crystal.[14–17] At the interface between two photonic crystals with overlapping bandgaps, there are surface electromagnetic OTSs that exhibit nonreciprocal behavior in magneto-photonic structures. Furthermore, a similar confined electromagnetic modes can also exist at the boundary between a metal layer and a Bragg mirror, which are called Tamm plasmon polaritons (TPPs).[18] When the medium in the Bragg mirror is a gyrotropic material, TPPs have nonreciprocal properties. The other types of such waves are surface plasmon-polaritons (SPPs),[19,20] which exist at interfaces separating metals and dielectrics. When the metal is MOMs, the time-reversal symmetry of the SPs is broken and the nonreciprocal wave propagation can be observed.[21,22] Although these two types of surface waves have different natures, their properties are quite similar.

In the magneto-photonic crystals, nonreciprocality of propagating waves can be switched by the one-way electromagnetic OTSs (or TTPs), which is based on an infinite or half infinite periodic structure. In reality, the properties of nonreciprocality could be diminished by the finite periodic structure. At the same time, the nanoscale magneto–optical layers are tightly linked in the magneto-photonic crystals, it is extremely difficult to magnetize magneto–optical layers by the external magnetic field. Furthermore, the anisotropic EM parameters in the magneto–optical mediums are not constant, and are regulated by the magnitude of magnetic field and frequencies of incident waves. The nonreciprocality is intensively related to EM parameters in the magneto–optical mediums, which have been seldom involved in previous researches. Therefore, it is necessary to search effective methods to realize and enhance nonreciprocality.

In this paper, a simple three-layer structure composed of anisotropic MOMs magnetized in the opposite directions and normal mediums is constructed, and the nonreciprocal propagation property is enhanced by nonreciprocal SPPs. The rest

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of this paper is organized as follows. First, the three-layer structure with MOMs is constructed, and reflection coefficient is conducted by the transfer matrix method.[23,24] Second, the numerical results and discussions associated with our purposes are presented. Finally, a conclusion is given in the last section.

## 2. Physical model and computational method

A one-dimensional (1D) structure with three layers is illustrated in Fig. 1, where $A$ and $A'$ layers are anisotropic MOMs, and $C$ layer is the normal material silicon dioxide ($SiO_2$). In the structure, $d_A$, $d_{A'}$, $d_C$ are the thicknesses of layers $A$, $A'$, and $C$, respectively. $B$ represents the external magnetic fields on the MOMs, where dot and cross represent the magnetic field direction along the positive and negative $y$ directions, respectively. In the Voigt geometry, the relative permittivity and permeability of layer $A$ and $A'$ can be expressed as

$$\bar{\bar{\varepsilon}} = \begin{vmatrix} \varepsilon_{r1} & 0 & i\varepsilon_{rg} \\ 0 & \varepsilon_{r1} & 0 \\ -i\varepsilon_{rg} & 0 & \varepsilon_{r2} \end{vmatrix}, \qquad \mu_r = 1. \tag{1}$$

Layers $A$ and $C$ are magnetized plasma materials, which the relative permittivity can be expressed as

$$\varepsilon_{r1} = 1 - \frac{\omega_{pe}^2}{\omega^2(1 \pm \frac{\omega_{le}}{\omega})}, \quad \varepsilon_{r2} = 1 - \frac{\omega_{pe}^2}{\omega^2},$$
$$\varepsilon_{rg} = -\frac{\omega_{pe}^2 \omega_{le}}{\omega^2(\omega \pm \omega_{le})}, \tag{2}$$

where $\omega$ is the incident wave angular frequency, and $\omega_{pe} = (ne^2/m\varepsilon_0)^{1/2}$ is the oscillation frequency of electric plasma, which is related to the number density of electrons $n$, the electronic charge $e$, electronic mass $m$, and the permittivity $\varepsilon_0$ in the vacuum. $\omega_{le} = eB/m$ is the gyrofrequency, which is related to the magnitude and direction of the additional static magnetic field $B$. If the direction of additional magnetic field is along the $y$ direction, then we take the minus sign in Eq. (2). Conversely, we take the plus sign in the formula.

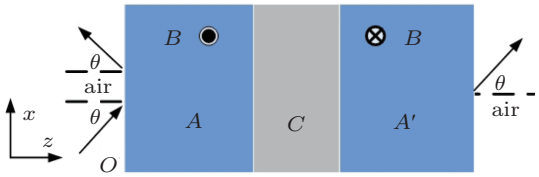



**Fig. 1.** The schematic diagram of 1D structure air/$ACA'$/air, composed of plasma layers $A$, $A'$, and normal material layer $C$.

For simplicity, a TM mode incident plane wave, $\boldsymbol{H}_y(x,z) = e^{i(k_x x + k_z z)}$, incident on the stratified medium, the total field in one layer can be written as:

$$\boldsymbol{H}_y(x,z) = \boldsymbol{H}_y^+(x,z) + \boldsymbol{H}_y^-(x,z).$$

$\boldsymbol{H}_y^+(x,z)$ and $\boldsymbol{H}_y^-(x,z)$ represent the wave propagates along the positive and negative $z$ directions, respectively, and their fields are related to those in neighboring regions by boundary conditions. According to the transfer matrix methods,[23,24] the fields of boundary in one region $i$ is connected to those in the adjacent region $j$ by the transfer matrix:

$$\begin{vmatrix} H_i^+ \\ H_i^- \end{vmatrix} = T_{ij} \begin{vmatrix} H_j^+ \\ H_j^- \end{vmatrix}, \tag{3}$$

where $T_{ij}$ is the transfer matrix of the adjacent layers $i$ and $j$, can be written as

$$T_{i,j} = \frac{1}{2N_i} \begin{vmatrix} N_i - M_i + N_j + M_j & N_i - M_i - N_j + M_j \\ N_i + M_i - N_j - M_j & N_i + M_i + N_j - M_j \end{vmatrix} \tag{4}$$

for anisotropic medium, where $N_l = k_{zl}/(\omega\varepsilon_0\varepsilon')$, $M_l = -ik_x\varepsilon_{rg}/(\omega\varepsilon_0\varepsilon')$, $\varepsilon' = \varepsilon_{rg}^2 - \varepsilon_{r1}^2$, and

$$k_{zl} = \sqrt{\frac{\omega_0^2}{c^2}\frac{\varepsilon_{r1}\varepsilon_{r2} - \varepsilon_{rg}^2}{\varepsilon_{r2}} - \frac{\varepsilon_{r1}}{\varepsilon_{r2}}k_x^2}$$

is the wave vector of $z$ axis in the layer $l$, and $k_x$ is the transverse wave vector along $x$ direction. If the medium is isotropic, $N_l$ and $M_l$ can be simplified by $\varepsilon_{rg} = 0$ and $\varepsilon_{r1} = \varepsilon_{r2}$. When the TM mode wave propagates through this multilayer structure, the incident, reflected, and transmitted electric fields are connected via a total transfer matrix

$$M = \sum P_i T_{ij} = \begin{vmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{vmatrix}, \tag{5}$$

where $P_i$ is the phase-shift factor of the one layer from front boundary to rear boundary, and defined as follows:

$$P_i = \begin{vmatrix} e^{-ik_{iz}d_i} & 0 \\ 0 & e^{ik_{iz}d_i} \end{vmatrix}, \tag{6}$$

where $d_i$ is thickness of the $i$-th layer. The total transmission and reflection coefficients $t$ and $r$ of the EM field through such a structure is given by

$$t = \frac{1}{|M_{11}|}, \qquad r = \frac{|M_{21}|}{|M_{11}|}, \tag{7}$$

where $M_{11}$ and $M_{21}$ are elements of the transfer matrix $M$.

According to Eq. (2), the Voigt permittivity in the gyroelectric medium, the function of the frequencies, is less than zero when the frequencies of incident waves are less than certain frequencies. Under this circumstance, the behaviors of anisotropic gyroelectric medium and SPPs in the boundaries between gyroelectric medium and normal medium can be stimulated. Furthermore, the asymmetry of the gyroparameters in two-sides gyroelectric medium is enlarged by the opposite magnetic fields, which enhance the nonreciprocal transmission of the electromagnetic waves.

## 3. Numerical results

To demonstrate the nonreciprocity in the designed structure, the transmission properties are numerically calculated when a plane wave is incident from left boundary of the structure. The medium parameters in the numerical simulations are chosen as: For medium in layer $C$, we choose material $SiO_2$, the relative permittivity $\varepsilon_r = 2.07$, the relative permeability $\mu_r = 1$; for gyroelectric medium in layers $A$ ($A'$), $n = 8 \times 10^{17}$ m$^{-3}$, $\omega_{pe} = 5 \times 10^{10}$ s$^{-1}$, $\omega_{le} = 1.76 \times 10^{11}$ s$^{-1}$, and relative permeability $\mu_r = 1$. Because the Voigt permittivity of gyroelectric medium is less then 0 when the frequencies of incident waves are less than 8 GHz, in the simulations we chose to use a frequency range from 2 GHz to 8 GHz.

### 3.1. The influence of the incident angle on nonreciprocity

First, we assume that a TM wave is incident on the PCs structure at different angles $\theta = 60°$, $45°$, and $30°$ from the boundaries, and we choose the external static magnetic field $B = 0.02$ T, the thickness of $d_A = d_{A'} = 25$ mm, $d_C = 30$ mm. Figure 2 shows the relationships between transmission coefficient and frequencies, where the solid line and dash line correspond to the forward ($k_x > 0$) and backward ($k_x < 0$) incidences, respectively. For incident angle $\theta = 60°$ in Fig. 2(a), there are two different transmission peaks, $f = 5.10673$ GHz for positive incidence and $f = 5.22093$ GHz for negative incidence. The results show that there are transmission nonreciprocity due to the asymmetric structure $A$ and $A'$ in the opposite external magnetic fields. Figures 2(b) and 2(c) also show two different transmission peaks for incident angle $45°$ and $30°$. As the incident angles decrease, there is also transmission nonreciprocity, and the two different transmission peaks shift right and broaden.

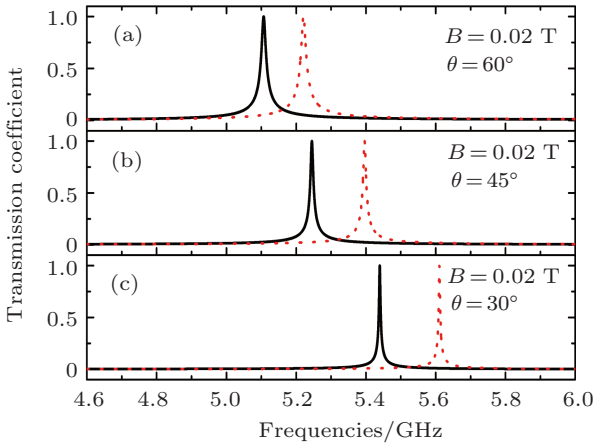



**Fig. 2.** The relationships between the transmission coefficient and the frequencies for different incident angles, where the solid line represents positive incidence, and dot line represents negative incidence. (a) incident angle $\theta = 60°$, (b) incident angle $\theta = 45°$, and (c) incident angle $\theta = 30°$.

To clearly show the transmission nonreciprocity, the field patterns of $H_z$ for the forward ($k_x > 0$) and backward ($k_x < 0$) incidences are shown in Fig. 3, where the incident angle is $60°$, and other conditions are the same as given in Fig. 2. Figures 3(a) and 3(b) show the field patterns of $H_z$ for frequency of $f = 5.10673$ GHz, when counter-propagating TM plane waves are incident from left and right boundaries. For the positive incidence, multi-layers look like a transparent medium, and the fields can completely pass through them. At the same time, there are strong fields in the interface between gyroelectric medium and normal medium and in the middle normal medium. In contrast, for the negative incidence, the transmitted waves are almost suppressed, and the fields cannot transmit through the mutli-layer. Then, the stationary waves in the incident region are formed by interactions between incident waves and reflective waves. For the frequency of $f = 5.22093$ GHz, the similar results are shown in Figs. 3(c) and 3(d), the negative propagating wave can transmit through the multi-layers and the positive incident waves are completely reflected. Thus, the nonreciprocal propagating properties are realized by the simple three layers.

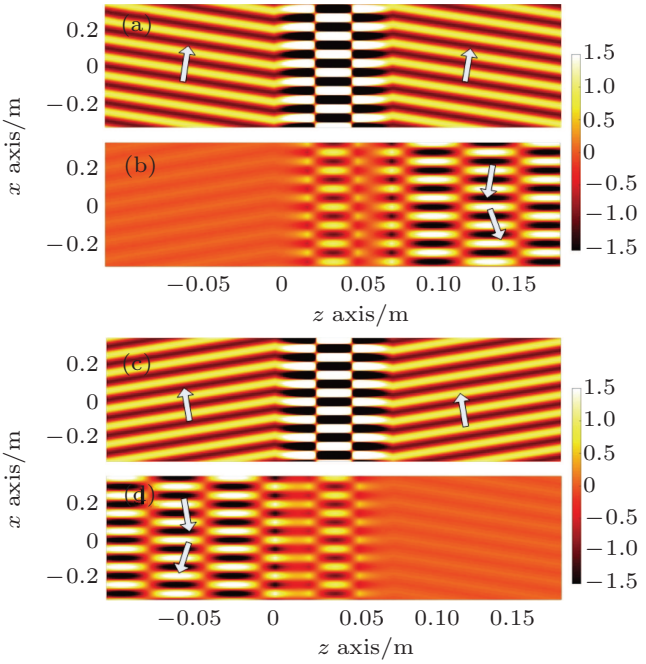



**Fig. 3.** The distributions of magnetic fields $H_y$ along $xz$ plane, where the external magnetic fields $B = 0.02$ T and incident angle is $60°$. (a) Positive incidence with $f = 5.10673$ GHz, (b) negative incidence with $f = 5.10673$ GHz, (c) negative incidence with $f = 5.22093$ GHz, and (d) positive incidence with $f = 5.22093$ GHz.

To further investigate the nonreciprocal transmission properties in the multi-layers, the distributions of magnetic fields $H_y$ along the $z$ direction with $x = 0$ has performed for incident angle $60°$ in Fig. 4, where the solid line and dot line represent $k_x > 0$ and $k_x < 0$ incidences, respectively, and the dash line represents the different layers. For positive incident frequency $f = 5.10673$ GHz, when the waves transmit through the muti-layers, as figure 4(a) shows: there are strong SPPs in the interface between the gyroelectric medium and

normal medium, and there appears resonant peak in the middle normal medium. For negative incidence at the same frequency, there are no SPPs in the interface and no resonant peak in the normal medium, which appears to be a one-way total transmission property due to nonreciprocity of the gyroelectric medium. For frequency $f = 5.22093$ GHz, the resonant peak appears in the multi-layers for negative incidence and the positive incidence is almost completely suppressed due to the nonreciprocity of gyroelectric medium.

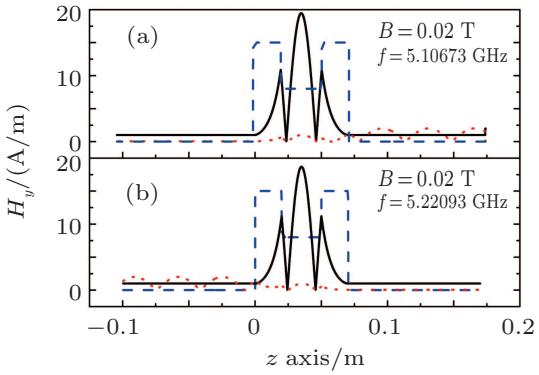



**Fig. 4.** The distributions of magnetic fields $H_y$ along the $z$ direction with $x = 0$, where the external magnetic fields $B = 0.02$ T and incident angle is 60°. (a) $f = 5.10673$ GHz, the solid and dot lines represent positive incidence and negative incidence, respectively, (c) $f = 5.22093$ GHz, the solid and dot lines represent negative incidence and positive incidence, respectively.

In the three-layer structure $ACA'$, the gyroelectric medium $A$ and $A'$ on both sides of normal medium $C$ constitute two asymmetric units $AC$ and $CA'$. At our working frequencies, the Voigt permittivities of the gyroelectric medium are negative, and the waves cannot be transmitted in the propagating direction due to imaginary propagation constant. But in a certain frequency, the unidirectional SPPs (also known as surface magneto-plasmons (SMPs)[22]) in the surface between gyroelectric medium and normal medium can be excited by the external fields in the bandgap, then the incident wave can completely propagate through the three-layer structure. On the contrary, when the wave at the same frequency is incident from the opposite direction, the SPPs are completely compressed or even removed in the interface, and incident wave is completed reflected.

#### 3.1.1. The influence of magnetic field *B* on nonreciprocity

Because the nonreciprocity of the structure is related to the external magnetic fields, we have investigated the transmitting properties of multi-layers for different magnetic fields, where the incident angle is 60°, and the other conditions are the same as given in Fig. 2. When the external fields $B$ increase from 0.2 T to 0.6 T, the gyroelectric components of gyroelectric medium largen, and nonreciprocity of structure is enhanced. The relationships between the transmission coefficient and the frequencies for different external magnetic fields are depicted in Fig. 5, where the solid line and dot line represent $k_x > 0$ and $k_x < 0$ incidences, respectively. This clearly shows the transmitting peak shifts to low frequencies for $k_x > 0$ case, and the transmitting peak shifts to high frequencies for $k_x < 0$ case, when the external magnetic field increases. That is to say, the distance of frequencies of counter-propagating waves are symmetrically broaden, and the nonreciprocal transmission properties increases with the increase of the external magnetic fields.

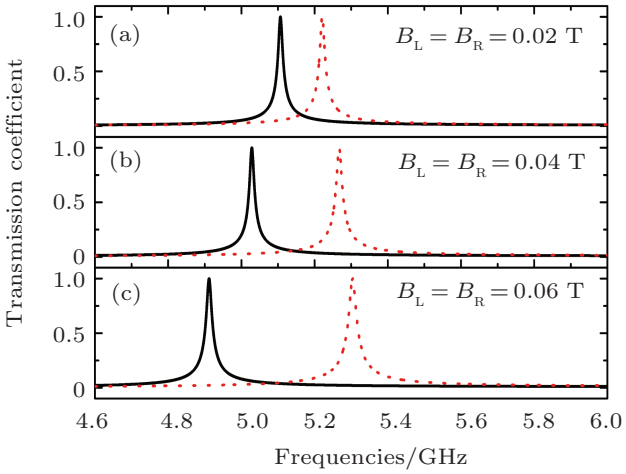



**Fig. 5.** The relationships between the transmission coefficients and the frequencies for different external magnetic fields with the incident angle $\theta = 60°$. The solid and dot lines represent positive and negative incidences, respectively. (a) $B = 0.02$ T, (b) $B = 0.04$ T, and (c) $B = 0.06$ T.

### 3.2. The influence of the thickness of layers on nonreciprocity

To take into account the thickness of layer $C$ between two gyroelectric mediums, we calculate the transmission coefficients and the results are shown in Fig. 6 for the case of different thicknesses of layer $C$. Based on this discussion, the behaviors of two gyroelectric mediums are similar to those of metal, and a resonant cavity $ACA'$ is constructed. The different thicknesses of layer $C$ decide the different resonant frequencies. Figure 6 shows the the relationship between transmission coefficients and frequencies for TM mode plane wave vectors $k_x > 0$ and $k_x < 0$. When the thickness of layer $C$ decreases from 30 mm to 20 mm, for positive incidence, the transmission peaks shift from $f = 5.10673$ GHz to $f = 6.60446$ GHz; for the negative incidence, the transmission peaks shift from $f = 5.22093$ GHz to $f = 6.81596$ GHz, and the distance of transmission peaks for counter-propagating waves broadens, which means that the nonreciprocity of the structure is improved with the decrease of thickness for layer $C$. Therefore, if the layer $C$ is consisted of multilayer with the same thickness and EM parameters, then a specific nonreciprocal transmission frequencies can be acquired by increasing or decreasing layers, which have potential applications in integrated circulators and isolators. In addition, because the layer $C$ is a normal

medium, in the hamburger structure $ACA'$, the properties transmission nonreciprocity can be realized by layer $C$ filled with other EM parameters.

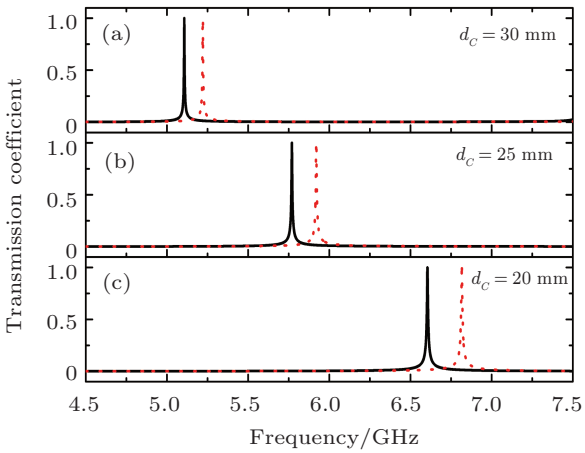



**Fig. 6.** The relationships between the transmission coefficients and the frequencies with different thicknesses of layer $C$, where the solid and dot lines represent positive and negative incidences, respectively. The incident angle $\theta$ is 60°, and the external magnetic fields $B$ is 0.02 T. (a) $d_C = 30$ mm, (b) $d_C = 25$ mm, and (c) $d_C = 20$ mm.

## 4. Conclusion

In this paper, the transmission nonreciprocity has been studied by a simple structure that consists of three layers filled with MOM and normal medium. When two layers with magneto–optical medium loaded in opposite external magnetic field, the time-reversal symmetry has been broken. Numerical results show that the nonreciprocal transmission peaks are influenced by the external magnetic fields, incident angles, and thickness of the normal layer. With the increasing of external magnetic fields and incident angle, the nonreciprocal transmission peaks shift to high frequencies, and the properties of the transmission nonreciprocity are enhanced. At the same time, with the decrease of thickness of the normal medium, the nonreciprocal transmission peaks also shift to high frequencies and the properties of the transmission nonreciprocity are also enhanced. Because the nonreciprocal properties can be easily realized and adjusted by the simple structure, this design has potential applications in integrated circulators and isolators.

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