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TUNABLE TE/TM WAVE SPLITTER USING A GYROTROPIC SLAB

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Abstract—A TE/TM wave splitter composed of a gyrotropic slab is proposed. We demonstrate theoretically that, when the working frequency is chosen to be within one of the two ranges, total reflection occurs at the boundary of a slab of gyrotropic medium for either TE or TM component of the incident waves. Tuning can be done by choosing the working frequency band or adjusting the applied magnetic field. Furthermore, within the TE-stop or TM-stop frequency region, if the incident angle is selected appropriately, the other polarized component of the wave is totally transmitted. And we also show that when the slab is thicker, there are more possibilities to satisfy the full-pass condition. Finite-element method simulations verified the theoretical results.

1. INTRODUCTION

A polarizer or polarization device is an essential component in many fiber optic communication and sensor systems, such as free-space optical switching networks [1], read-write magneto-optic data storage systems [2], and polarization-based imaging systems [3]. The principle of a polarizer is to attenuate the TE (or pseudo-TE) or TM (or pseudo-TM) modes, resulting in a TM-pass or TE-pass polarizer [4]. In

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general, polarizers can be classified into the following types: dichroic polarizers, anisotropic crystal polarizers, Brewster angle polarizers, and wire-grid polarizers [5].

In this paper, we present the theoretical analysis of a polarizer using gyrotropic medium. Gyrotropic medium is anisotropic and nonreciprocal under an applied DC magnetic field. The characteristics of electromagnetic waves propagation in gyrotropic plasmas have been theoretically investigated in many literatures. The magnetoplasma modes in Voigt, perpendicular, and Faraday configurations have been studied by Kushwaha and Halevi [6–8], Gillies and Hlawiczka have done some researches on gyrotropic waveguide in detail [9–13], and dyadic Green's functions for gyrotropic medium have been investigated by Eroglu as well as Li [14–16]. There are also some studies focusing upon the effects of magnetic field on semiconducting plasma slab and negatively refracting surfaces [17, 18]. Furthermore, propagation and scattering characteristics in gyrotropic systems [14, 19–23] and surface modes at the interface of a special gyrotropic medium [24] have been investigated extensively.

A polarizer using the gyrotropic medium here can serve as TE-stop or TM-stop depending on the working frequency band. Moreover, if the incident angle is selected appropriately, this simple structure can further realize the full-pass of the other mode, resulting in a TE/TM splitter. The result is verified by the numerical simulation based on the finite-element method.

This paper is arranged as follows. In Section 2, the theory is presented and it includes the analytic formulas of the reflection and transmission coefficients for both TE and TM modes. In Section 3, we give examples that illustrate TE and TM waves transmitted and reflected by the gyrotropic slab at different frequency and incident angle. Finally, concluding remarks are given in Section 4.

2. THEORETICAL ANALYSIS

The permittivity of a gyrotropic medium can be written as a tensor:

$$\bar{\bar{\varepsilon}}_2 = \begin{bmatrix} \varepsilon_{xx} & i\varepsilon_g & 0 \\ -i\varepsilon_g & \varepsilon_{yy} & 0 \\ 0 & 0 & \varepsilon_{zz} \end{bmatrix}, \tag{1}$$

where elements are given by

$$\varepsilon_{xx} = \varepsilon_{yy} = \varepsilon_\infty \left(1 - \frac{\omega_p^2}{\omega^2 - \omega_c^2}\right), \tag{2.1}$$

$$\varepsilon_{zz} = \varepsilon_\infty \left(1 - \frac{\omega_p^2}{\omega^2}\right), \tag{2.2}$$

$$\varepsilon_g = \varepsilon_\infty \left[-\frac{\omega_p^2 \omega_c}{\omega\left(\omega^2 - \omega_c^2\right)}\right]. \tag{2.3}$$

Here, $\omega_p = \sqrt{N q_e^2 / m_{\mathit{eff}} \varepsilon_\infty}$ and $\bar{\omega}_c = q_e \bar{B}_0 / m_{\mathit{eff}}$ are the plasma and cyclotron frequencies respectively, ε_∞ is the background permittivity, N is the electron density, m_{eff} is the effective mass, and q_e is the electron charge.

We consider the geometry shown in Fig. 1, where a plane wave is incident from an isotropic medium into an infinite gyrotropic slab at an oblique angle θ_i with respect to the normal of the interface. The gyrotropic slab of thickness d is arranged in the Voigt configuration, where the external magnetic field $\bar{B}_0$ is in $+z$ direction.

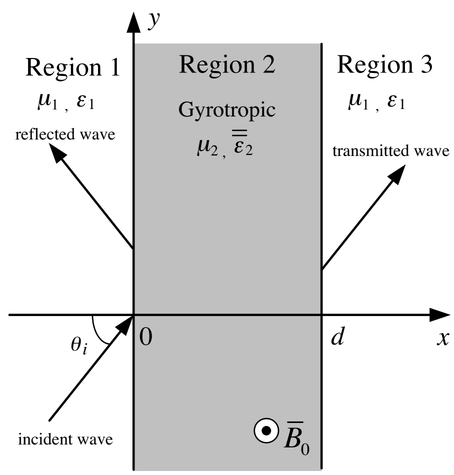

Figure 1. Gyrotropic slab with thickness d in an isotropic medium. Region 1 and Region 3 are the same isotropic medium, with permittivity ε_1 and permeability μ_1. Region 2 is a gyrotropic medium with $\bar{\bar{\varepsilon}}_2$ and μ_2. An applied magnetic field $\bar{B}_0$ is in $+z$ direction, parallel to the interfaces and perpendicular to the plane of incidence (Voigt configuration).

It is known that in the Voigt configuration, waves can be decoupled into TE and TM modes with different dispersion relation [14, 18, 25]. With wave vectors $\bar{k}_1 = \pm\hat{x}k_{1x} + \hat{y}k_y$ in the isotropic medium and $\bar{k}_2^{TE} = \pm\hat{x}k_{2x}^{TE} + \hat{y}k_y$ for TE modes or $\bar{k}_2^{TM} = \pm\hat{x}k_{2x}^{TM} + \hat{y}k_y$ for TM modes in the gyrotropic medium, the dispersion relations of the two media can be expressed as

$$\text{isotropic: } k_y^2 + k_{1x}^2 = \omega^2 \mu_1 \varepsilon_1, \tag{3}$$

$$\text{TE modes in gyrotropic: } k_y^2 + \left(k_{2x}^{TE}\right)^2 = \omega^2 \mu_2 \varepsilon_{zz}, \tag{4}$$

$$\text{TM modes in gyrotropic: } k_y^2 + \left(k_{2x}^{TM}\right)^2 = \omega^2 \mu_2 \varepsilon_V, \tag{5}$$

where the Voigt permittivity for TM modes is introduced as

$$\varepsilon_V = \frac{\varepsilon_{xx}^2 - \varepsilon_g^2}{\varepsilon_{xx}}. \tag{6}$$

It is of interest to note that the gyrotropic medium behaves differently for the two modes due to the different permittivity components [ε_{zz} for TE mode in Eq. (4), ε_V for TM mode in Eq. (5)] arisen from the applied magnetic field $\bar{B}_0$. Furthermore, according to Eqs. (2.1)–(2.3), and (6), we can see that the two permittivities have different frequency dependence. We show the relative permittivities of a gyrotropic medium for TE and TM modes versus frequency in Fig. 2. Corresponding to TE waves, ε_{zz} is not influenced by the applied magnetic field. It monotonically increases with the frequency and has a plasma frequency ω_p. For TM modes, ε_V is affected by the gyrotropy. The existence of the applied magnetic field splits ε_V into two branches which are separated by frequency $\omega_H = \sqrt{\omega_c^2 + \omega_p^2}$. The corresponding effective plasma frequencies for the two branches can be expressed as [26]

$$\omega_{p\pm} = \frac{1}{2}\left(\pm\omega_c + \sqrt{\omega_c^2 + 4\omega_p^2}\right). \tag{7}$$

For nonzero applied magnetic field $\bar{B}_0$, ω_c is nonzero and $\omega_{p-} < \omega_p < \omega_H < \omega_{p+}$, thus we can get two frequency bands in which one permittivity is negative and the other is positive, shown in Fig. 2. That is, in frequency band A ($\omega_{p-} < \omega < \omega_p$), $\varepsilon_{zz} < 0$ while $\varepsilon_V > 0$; in frequency band B ($\omega_H < \omega < \omega_{p+}$), $\varepsilon_{zz} > 0$ while $\varepsilon_V < 0$.

When the working frequency is selected to be in the band A or band B, i.e., the signs of the equivalent permittivities for the two modes are different, the gyrotropic slab can be used as a linear polarizer, because total reflection occurs for either TE or TM modes and we can consider that the transmitted wave contains only one polarized component. For instance, in frequency band A, ε_{zz} for TE modes is negative, making k_{2x}^{TE} become purely imaginary for any real value of $k_y < \omega\sqrt{\mu_1\varepsilon_1}$ [Eqs. (3) and (4)]. Thus, for TE waves, total reflection occurs at the interface and the waves become evanescent in the gyrotropic slab. On the other hand, ε_V for TM modes is positive, and k_{2x}^{TM} is real. Hence in region 3, we can receive the TM waves transmitted by the slab but little energy of TE waves from the region 1. That means we can consider frequency band A as the TE-stop band. Similarly, frequency band B where $\varepsilon_V < 0$ and $\varepsilon_{zz} > 0$ can be considered as the TM-stop band. Hence, when the working frequency is in the band either A or B, the gyrotropic slab is qualitatively a linear polarizer, because the transmitted wave is either TM or TE polarized. However, the transmittance may be low, and we need to find out the full-pass condition, the condition for total transmission.

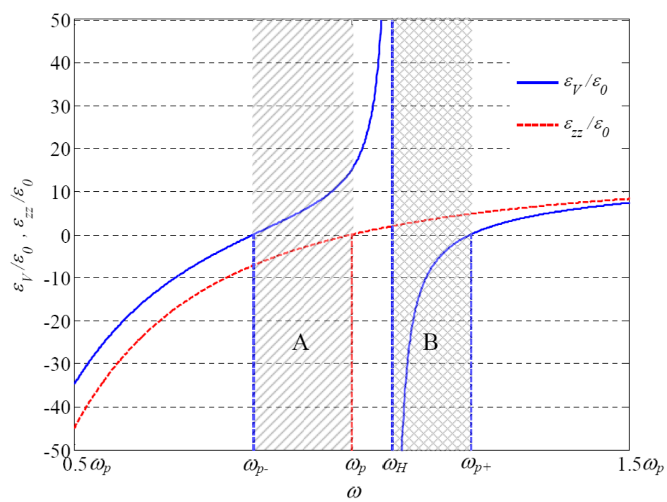

Figure 2. The relative permittivities of a gyrotropic medium (InSb with an applied magnetic field $\bar{B}_0 = +\hat{z}0.4\,\mathrm{T}$) for TE and TM waves versus frequency. $\varepsilon_{zz}/\varepsilon_0$ (in red dashed line) is the relative permittivity for TE modes, and $\varepsilon_V/\varepsilon_0$ (in blue solid line) is for TM modes. In frequency band A ($\omega_{p-} < \omega < \omega_p$), $\varepsilon_{zz} < 0$ while $\varepsilon_V > 0$; in frequency band B ($\omega_H < \omega < \omega_{p+}$), $\varepsilon_{zz} > 0$ while $\varepsilon_V < 0$.

Determined by the Maxwell equations and the boundary conditions, the transmission and reflection coefficients for TE waves can be written as

$$T^{TE} = \frac{1}{\cos(k_{2x}^{TE}d) - i\sin(k_{2x}^{TE}d)\left\{\left[\left(k_{2x}^{TM}\right)^2 + q^2k_{1x}^2\right]\Big/\left(2qk_{1x}k_{2x}^{TE}\right)\right\}}, \quad (8)$$

$$R^{TE} = \frac{-i\sin\left(k_{2x}^{TE}d\right)\left\{\left[q^2k_{1x}^2 - \left(k_{2x}^{TM}\right)^2\right]\Big/\left(2qk_{1x}k_{2x}^{TE}\right)\right\}}{\cos\left(k_{2x}^{TE}d\right) - i\sin\left(k_{2x}^{TE}d\right)\left\{\left[\left(k_{2x}^{TM}\right)^2 + q^2k_{1x}^2\right]\Big/\left(2qk_{1x}k_{2x}^{TE}\right)\right\}}, \quad (9)$$

where

$$q = \frac{\mu_2}{\mu_1}. \quad (10)$$

For TM waves, the transmission and reflection coefficients are [27]

$$T^{TM} = \frac{1}{\cos\left(k_{2x}^{TM}d\right) - i\sin\left(k_{2x}^{TM}d\right)\left\{\left[\left(k_{2x}^{TM}\right)^2 + \sigma^2k_{1x}^2 + \tau^2k_y^2\right]\Big/\left(2\sigma k_{1x}k_{2x}^{TM}\right)\right\}}, \quad (11)$$

$$R^{TM} = \frac{\sin\left(k_{2x}^{TM}d\right)\left\{\tau k_y\Big/k_{2x}^{TM} - i\left[\sigma^2k_{1x}^2 - \tau^2k_y^2 - \left(k_{2x}^{TM}\right)^2\right]\Big/\left(2\sigma k_{1x}k_{2x}^{TM}\right)\right\}}{\cos\left(k_{2x}^{TM}d\right) - i\sin\left(k_{2x}^{TM}d\right)\left\{\left[\left(k_{2x}^{TM}\right)^2 + \sigma^2k_{1x}^2 + \tau^2k_y^2\right]\Big/\left(2\sigma k_{1x}k_{2x}^{TM}\right)\right\}}, \quad (12)$$

where the parameters σ and τ are dimensionless and are defined as

$$\sigma = \frac{\varepsilon_V}{\varepsilon_1}, \text{ and } \tau = \frac{\varepsilon_g}{\varepsilon_{xx}}. \quad (13)$$

According to Eqs. (8) and (9), to make the slab full-pass for TE wave, the transmission coefficient should be 1 and reflection coefficient should be 0, thus

$$k_{2x}^{TE}d = m\pi \quad (m = 1, 2, 3, \ldots). \quad (14)$$

Similarly, based on Eqs. (11) and (12), we can get the full-pass condition for TM wave

$$k_{2x}^{TM}d = m\pi \quad (m = 1, 2, 3, \ldots). \quad (15)$$

According to the dispersion relations of the two media, Eqs. (3), (4), and (5), we can rewrite the full-pass condition in terms of incident angle

$$\sin\theta_i = \sqrt{\frac{\mu_2\varepsilon'}{\mu_1\varepsilon_1} - \frac{(m\pi)^2}{\omega^2\mu_1\varepsilon_1 d^2}} \quad (m = 1, 2, 3, \ldots), \quad (16)$$

where ε' denotes the corresponding permittivities of TE or TM modes. For TE full-pass condition, $\varepsilon' = \varepsilon_{zz}$, and $\varepsilon' = \varepsilon_V$ for TM full-pass condition.

Combined with TM-stop or TE-stop frequency band, we can get a TM/TE splitter with total reflection for one wave and total transmission for the other, and we can determine which wave to stop by choosing the working frequency band. When the working frequency is in frequency band A, the gyrotropic slab works as a TE-stop linear polarizer whose output is TM wave. Furthermore, if the incident angle is chosen to satisfy the full-pass condition [Eq. (16)], the slab enables the full transmission of TM wave. On the contrary, when the working frequency is in band B, the slab is a TM-stop polarizer and can transmit TE wave totally under the full-pass condition.

3. RESULT AND DISCUSSION

Here, we present some numerical simulations to verify the above theoretical results. We consider an indium antimony (InSb) slab in vacuum. The material parameters used in the computation are: $\mu_1 = \mu_2 = \mu_0$, $\varepsilon_1 = \varepsilon_0$, $\varepsilon_\infty = 15\varepsilon_0$, $N = 10^{22}\,\mathrm{m}^{-3}$, and $m_{eff} = 0.015\,m_0 = 0.13664 \times 10^{-31}\,\mathrm{kg}$ [28, 29]. Hence, $\omega_p = 1.19 \times 10^{13}\,\mathrm{rad/s}$ ($f_p = 1.89 \times 10^{12}\,\mathrm{Hz}$) and $\omega_c/\omega_p = 0.98B_0$. Suppose that the external magnetic field $\bar{B}_0 = +\hat{z}0.4\,\mathrm{T}$, we can get $\omega_{p-} = 0.823\omega_p$, $\omega_H = 1.074\omega_p$, and $\omega_{p+} = 1.215\omega_p$. Thus, the TE-stop frequency band A is $0.823\omega_p < \omega < \omega_p$ ($1.56\,\mathrm{THz} < f < 1.89\,\mathrm{THz}$); while the TM-stop band B is $1.074\omega_p < \omega < 1.215\omega_p$ ($2.03\,\mathrm{THz} < f < 2.30\,\mathrm{THz}$). Finite-element method is used to simulate the interaction of a Gaussian beam by a slab of gyrotropic medium with different frequencies and incident angles, and the PML absorbing boundary condition is applied to absorb outgoing waves.

In Fig. 3, we show the reflection and transmission of a Gaussian beam incident from the lower left at a working frequency of $0.85\omega_p$ ($f = 1.61\,\mathrm{THz}$), in the TE-stop frequency band A. Fig. 3(a) and Fig. 3(b) show the real part of electric field's z component in the xy plane generated by the TE incident wave; while Fig. 3(c) and Fig. 3(d) show the real part of magnetic field's z component with a TM incidence. The incident angle in Fig. 3(a) and Fig. 3(c) is 45 degree and is 30.25 degree in Fig. 3(b) and Fig. 3(d), and the latter satisfies the full-pass condition in Eq. (16). We can see that, for TE waves, total reflection occurs and little is transmitted, no matter what the incident angle is. In fact, the energy out flow from the slab is less than $10^{-4}\%$ in both Fig. 3(a) and Fig. 3(b). Hence, we can consider it as TE-stop. When the incident beam is TM mode, the transmission and reflection is sensitive to the incident angle. In Fig. 3(c), when the incident angle is 45 degree, the energy transmitted by the slab is about 76.51% and the reflected energy is 23.49%. In Fig. 3(d), up to 99.37% energy is transmitted and only 0.63% is reflected. The cause of nonzero reflection is due to the characteristic of the Gaussian beam, the deviation of the incident angle.

Here, we also show the cases of $1.15\omega_p$ ($f = 2.18\,\mathrm{THz}$, in the TM-stop frequency band B) in Fig. 4. Fig. 4(a) and Fig. 4(b) show the TE cases; while Fig. 4(c) and Fig. 4(d) are for TM incidence.

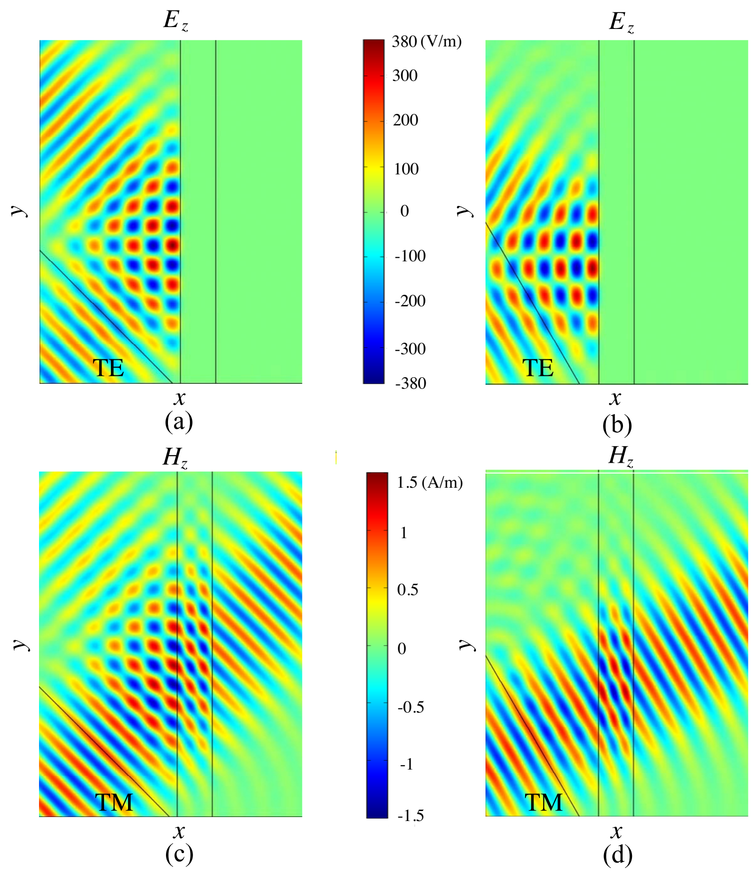

Figure 3. The reflection and transmission of a Gaussian beam incident from the lower left with a gyrotropic (InSb with an applied magnetic field $\bar{B}_0 = +\hat{z}0.4\,\mathrm{T}$) slab at a working frequency of $0.85\omega_p$. The thickness of the slab $d = 1.5\lambda_p = 3\pi c/\omega_p = 2.374 \times 10^{-4}\,\mathrm{m}$. (a) E_z of an incident TE wave with the incident angle $\theta_i = 45°$; (b) E_z of an incident TE wave with the incident angle $\theta_i = 30.25°$; (c) H_z of an incident TM wave with the incident angle $\theta_i = 45°$; (d) H_z of an incident TM wave with the incident angle $\theta_i = 30.25°$. Then (d) has the full-pass condition satisfied.

The incident angle in Fig. 4(a) and Fig. 4(c) is 45 degree; while 52.73 degree in Fig. 4(b) and Fig. 4(d), which satisfies the full-pass condition in Eq. (16). When the incident beam is TE mode, the transmission and reflection is sensitive to the incident angle. In Fig. 4(a), when the incident angle is 45 degree, the energy transmitted by the slab is about 87.31% and the reflected energy is 12.69%. In Fig. 4(b), 99.17% energy is transmitted and 0.83% is reflected. And the nonzero

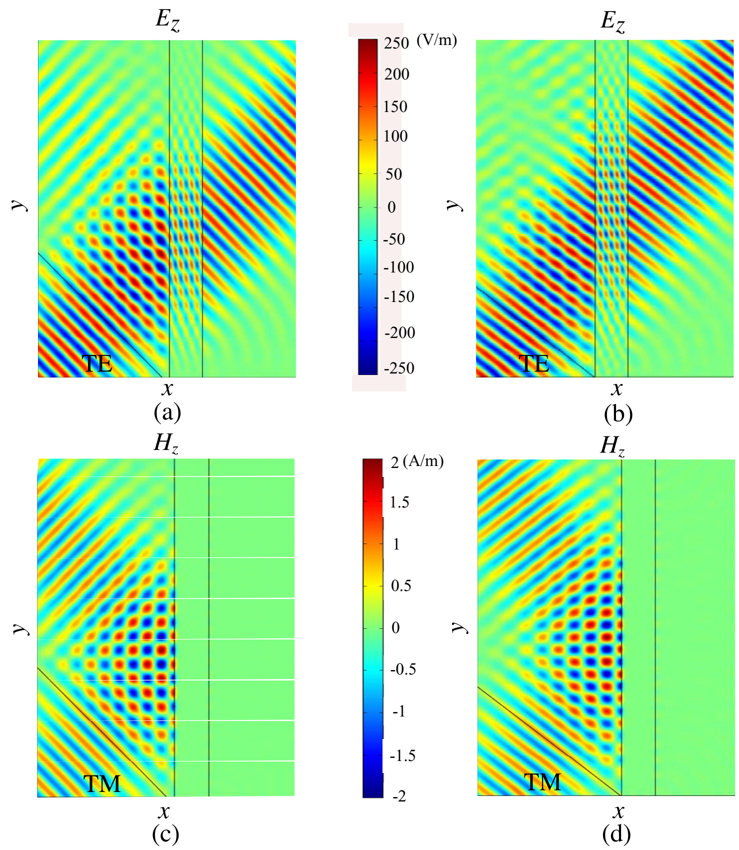

Figure 4. The reflection and transmission of a Gaussian beam by the same gyrotropic slab as that in Fig. 3 at a working frequency of $1.15\omega_p$. (a) E_z of an incident TE wave with the incident angle $\theta_i = 45°$; (b) E_z of an incident TE wave with the incident angle $\theta_i = 52.73°$; (c) H_z of an incident TM wave with the incident angle $\theta_i = 45°$; (d) H_z of an incident TM wave with the incident angle $\theta_i = 52.73°$. Then (b) has the full-pass condition satisfied.

reflection is also due to the nature of the Gaussian beam, the small variation of the incident angle. For TM case, the energy outflow from the slab is $1.43 \times 10^{-3}\%$ in Fig. 4(c), while $1.10 \times 10^{-2}\%$ in Fig. 4(d). Hence, we can consider the gyrotropic slab in this frequency band to be TM-stop, and when the appropriate incident angle is selected to satisfy the full-pass condition, it can ensure the full transmission of TE mode.

Furthermore, we want to mention that the splitter is tunable. We can change the frequency bands by adjusting the applied magnetic field. According to Eq. (7), the range of TE-stop frequency band A or TM-stop band B is determined by the plasma frequency ω_p, as well as ω_c, the cyclotron frequency. Both of them are related to the parameters of gyrotropic medium and ω_c is proportional to the applied magnetic field. So we can expand both of the frequency bands by increasing the external magnetic field. For example, when the applied magnetic field is 0.6 T, the TE-stop band A is $0.748\omega_p < \omega < \omega_p$; while the TM-stop band B is $1.160\omega_p < \omega < 1.336\omega_p$, both wider than those of 0.4 T.

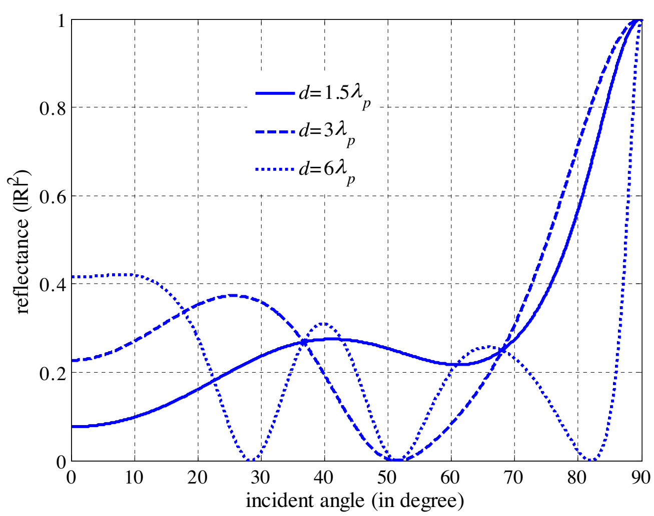

Figure 5. The reflectance of TM waves versus incident angle. The applied magnetic field is 0.4 T and the working frequency $0.90\omega_p$. The parameters of gyrotropic medium are the same as Fig. 3. When thickness of the slab $d = 1.5\lambda_p$, there is no angle for zero reflectance, which means no solution to the full-pass condition. When $d = 3\lambda_p$, there is one angle for the full transmission: $\theta_i = 51.50°$; while $d = 6\lambda_p$, the number of solutions becomes 3: $\theta_i = 28.35°$, $51.50°$ and $82.05°$.

Moreover, the full-pass condition is sensitive to d, the thickness of the slab. Taking band A as an example, when the applied magnetic field is 0.4 T and the working frequency is $0.90\omega_p$ we plot the reflectance of TM wave versus incident angle in Fig. 5. When the reflectance is zero, TM waves can be transmitted fully by the slab. From Fig. 5, we can see that when thickness is too small, there may not be any zero reflectance regardless of the incident angle, which means no solution to the full-pass condition. When the thickness is larger, there may be more than one incident angles to satisfy the full-pass of TM waves. The thicker the slab is, the more possibilities to find the solution to full-pass.

4. CONCLUSION

In summary, we use a gyrotropic slab as a tunable TE/TM splitter. It can serve as a TE-stop or a TM-stop linear polarizer depending on different working frequency. Besides, it can further transmit the other wave totally if the incident angle is chosen to satisfy the full-pass condition. The frequency band is closely related to the parameters of gyrotropic medium, which can be changed by adjusting the external magnetic field. And the full-pass condition is easier to be satisfied when the thickness of the slab is larger.

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REFERENCES

1. McCormick, F. B., F. A. P. Tooley, T. J. Cloonan, J. L. Brubaker, A. L. Lentine, R. L. Morrison, S. J. Hinterlong, M. J. Herron, S. L. Walker, and J. M. Sasian, "Experimental investigation of a free-space optical switching network by using symmetric self-electro-optic-effect devices," *Appl. Opt.*, Vol. 31, 5431–5446, 1992.
2. Ojima, M., A. Saito, T. Kaku, M. Ito, Y. Tsunoda, S. Takayama, and Y. Sugita, "Compact magnetooptical disk for coded data storage," *Appl. Opt.*, Vol. 25, 483–489, 1986.

3. Kunstmann, P. and H. J. Spitschan, "General complex amplitude addition in a polarization interferometer in the detection of pattern differences," *Opt. Commun.*, Vol. 4, 166–168, 1971.
4. Li, G. and A. Xu, "Analysis of the TE-pass or TM-pass metal-clad polarizer with a resonant buffer layer," *J. Lightwave Technol.*, Vol. 26, 1234–1241, 2008.
5. Dummer, D. J., S. G. Kaplan, L. M. Hanssen, A. S. Pine, and Y. Zong, "High-quality Brewster's angle polarizer for broadband infrared application," *Appl. Opt.*, Vol. 37, 1194–1204, 1998.
6. Kushwaha, M. S. and P. Halevi, "Magnetoplasmons in thin films in the Voigt configuration," *Phys. Rev. B*, Vol. 36, 5960–5967, 1987.
7. Kushwaha, M. S. and P. Halevi, "Magnetoplasmons in thin films in the perpendicular configuration," *Phys. Rev. B*, Vol. 38, 12428–12435, 1988.
8. Kushwaha, M. S. and P. Halevi, "Magnetoplasma modes in thin films in the Faraday configuration," *Phys. Rev. B*, Vol. 35, 3879–3889, 1987.
9. Gillies, J. R. and P. Hlawiczka, "TE and TM modes in gyrotropic waveguides," *J. Phys. D: Appl. Phys.*, Vol. 9, 1315–1322, 1976.
10. Gillies, J. R. and P. Hlawiczka, "Elliptically polarized modes in gyrotropic waveguides. II. An alternative treatment of the longitudinally magnetized case," *J. Phys. D: Appl. Phys.*, Vol. 10, 1891–1904, 1977.
11. Hlawiczka, P., "Elliptically polarized modes in gyrotropic waveguides," *J. Phys. D: Appl. Phys.*, Vol. 9, 1957–1965, 1976.
12. Hlawiczka, P., "A gyrotropic waveguide with dielectric boundaries: The longitudinally magnetised case," *J. Phys. D: Appl. Phys.*, Vol. 11, 1157–1166, 1978.
13. Hlawiczka, P., "The gyrotropic waveguide with a normal applied DC field," *J. Phys. D: Appl. Phys.*, Vol. 11, 1941–1948, 1978.
14. Eroglu, A. and J. K. Lee, "Wave propagation and dispersion characteristics for a nonreciprocal electrically gyrotropic medium," *Progress In Electromagnetics Research*, PIER 62, 237–260, 2006.
15. Li, L. W., N. H. Lim, and J. A. Kong, "Cylindrical vector wave function representation of Green's dyadic in gyrotropic bianisotropic media," *Journal of Electromagnetic Waves and Applications*, Vol. 17, 1589–1591, 2003.
16. Li, L. W., N. H. Lim, W. Y. Yin, and J. A. Kong, "Eigenfunctional expansion of dyadic Green's functions in gyrotropic media using cylindrical vector wave functions — Abstract," *Journal*

of Electromagnetic Waves and Applications, Vol. 17, 1731–1733, 2003.

17. Ivanov, S. T. and N. I. Nikolaev, "Magnetic-field effect on wave dispersion in a free semiconductor plasma slab," *J. Phys. D: Appl. Phys.*, Vol. 32, 430–439, 1999.
18. Boardman, A., N. King, Y. Rapoport, and L. Velasco, "Gyrotropic impact upon negatively refracting surfaces," *New J. Phys.*, Vol. 7, 1–24, 2005.
19. Zhang, M., L. W. Li, T. S. Yeo, and M. S. Leong, "Scattering by a gyrotropic bianisotropic cylinder of arbitrary cross section: An analysis using generalized multipole technique — Abstract," *Journal of Electromagnetic Waves and Applications*, Vol. 17, 1049–1051, 2003.
20. Yin, W. Y., L. W. Li, and M. S. Leong, "Scattering from multiple bianisotropic cylinders and their modeling of cylindrical objects of arbitrary cross-section — Abstract," *Journal of Electromagnetic Waves and Applications*, Vol. 14, 611–612, 2000.
21. Tan, E. L. and S. Y. Tan, "Cylindrical vector wave function representations of electromagnetic fields in gyrotropic bianisotropic media," *Journal of Electromagnetic Waves and Applications*, Vol. 13, 1461–1476, 1999.
22. Bass, F. and L. Resnick, "Spatial and temporal rotation of the polarization plane of electromagnetic waves reflected from and transmitted through a gyrotropic plate," *Journal of Electromagnetic Waves and Applications*, Vol. 17, 1131–1137, 2003.
23. Censor, D. and M. D. Fox, "Polarimetry in the presence of various external reflection and retrodirection mirroring mechanisms, for chiral and gyrotropic media," *Journal of Electromagnetic Waves and Applications*, Vol. 11, 297–313, 1997.
24. Huang, H., Y. Fan, B.-I. Wu, F. Kong, and J. A. Kong, "Surface modes at the interfaces between isotropic media and uniaxial plasma," *Progress In Electromagnetics Research*, PIER 76, 1–14, 2007.
25. Huang, H., Y. Fan, F. Kong, B.-I. Wu, and J. A. Kong, "Influence of external magnetic field on a symmetrical gyrotropic slab in terms of Goos-Hänchen shifts," *Progress In Electromagnetics Research*, PIER 82, 137–150, 2008.
26. Kong, F., K. Li, H. Huang, B.-I. Wu, and J. A. Kong, "Analysis of the surface magnetoplasmon modes in the semiconductor slit waveguide at terahertz frequencies," *Progress In Electromagnetics Research*, PIER 82, 257–270, 2008.

27. Huang, H., Y. Fan, B.-I. Wu, and J. A. Kong, "Positively and negatively large Goos-Hänchen lateral displacements from a symmetric gyrotropic slab," accepted for publication in *Appl. Phys. A: Mater.*, 2008.
28. Brion, J. J., R. F. Wallis, A. Hartstein, and E. Burstein, "Theory of surface magnetoplasmons in semiconductors," *Phys. Rev. Lett.*, Vol. 28, 1455–1458, 1972.
29. Remer, L., E. Mohler, W. Grill, and B. Lüthi, "Nonreciprocity in the optical reflection of magnetoplasmas," *Phys. Rev. B*, Vol. 30, 3277–3282, 1984.