A polarized beam splitter using an anisotropic medium slab

Hailu Luo, Weixing Shu, Fei Li, and Zhongzhou Ren

Department of Physics, Nanjing University, Nanjing 210008, China

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Abstract

The propagation of electromagnetic waves in the anisotropic medium with a single-sheeted hyperboloid dispersion relation is investigated. It is found that in such an anisotropic medium E- and H-polarized waves have the same dispersion relation, while E- and H-polarized waves exhibit opposite amphoteric refraction characteristics. E- (or H-) polarized waves are positively refracted whereas H- (or E-) polarized waves are negatively refracted at the interface associated with the anisotropic medium. By suitably using the properties of anomalous refraction in the anisotropic medium it is possible to realize a very simple and very efficient beam splitter to route the light. It is shown that the splitting angle and the splitting distance between E- and H- polarized beam is the function of anisotropic parameters, incident angle and slab thickness.

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*Author to whom correspondence should be addressed. E-mail: hailulu@sohu.com
I. INTRODUCTION

Polarization beam splitter is an important device in optical systems, such as polarization-independent optical isolators and optical switches [1, 2]. A conventional polarization beam splitter is made of a nonmagnetic anisotropic crystal or a multi-layer transparent material [3, 4, 5]. The separation between E- and H- polarized beams produced by these conventional methods is typically limited by the small splitting angle. While a large beam splitting angle and splitting distance are preferable for practical applications, especially in the field of optical communication systems.

In general, E- and H- polarized waves propagate in different directions in an anisotropic medium. For a regular anisotropic medium, all tensor elements of permittivity $\varepsilon$ and permeability $\mu$ should be positive. The recent advent of a new class of material with negative permittivity and permeability has attained considerable attention [6, 7, 8, 9, 10]. Recently, Lindell et al. [11] have shown that anomalous negative refraction can occur at an interface associated with an anisotropic media, which does not necessarily require that all tensor elements of $\varepsilon$ and $\mu$ have negative values. The studies of such anisotropic media have recently received much interest and attention [12, 13, 14, 15, 16, 17, 18, 19, 20]. Although E- and H-polarized waves can present the amphoteric refraction in conventional nonmagnetic anisotropic crystal [16], the splitting angle is very small. A question naturally arise: whether there exists a large splitting angle and splitting distance, when E- and H-polarized waves propagating in certain anisotropic media.

In this paper we investigate the propagation of electromagnetic waves in an anisotropic material with a single-sheeted hyperboloid dispersion relation. We show that E- (or H-) polarized beam is positively refracted whereas H- (or E-) polarized beam is negatively refracted at the interface associated with the anisotropic media. There exists both a large splitting angle and splitting distance, when E- and H-polarized waves in the special anisotropic media. We present a design of polarization beam splitters based on the anomalous refraction in the anisotropic medium. To match the boundary conditions, the material parameters of the anisotropic medium can be designed.
FIG. 1: E- and H-polarized waves have the same single-sheeted hyperboloid dispersion relation.

II. DISPERSION RELATIONS OF AN ANISOTROPIC MEDIA

Before we consider the beam splitter structure, we first analyze the dispersion relation of the anisotropic medium. For anisotropic materials one or both of the permittivity and permeability are second-rank tensors \[22, 23\]. To simplify the proceeding analysis, we assume the permittivity and permeability tensors are simultaneously diagonalizable:

\[
\begin{align*}
\varepsilon &= \begin{pmatrix}
\varepsilon_x & 0 & 0 \\
0 & \varepsilon_y & 0 \\
0 & 0 & \varepsilon_z
\end{pmatrix}, \quad 
\mu = \begin{pmatrix}
\mu_x & 0 & 0 \\
0 & \mu_y & 0 \\
0 & 0 & \mu_z
\end{pmatrix},
\end{align*}
\]

where \(\varepsilon_i\) and \(\mu_i\) are the permittivity and permeability constants in the principal coordinate system \((i = x, y, z)\).

We choose the \(z\) axis to be normal to the interface, and the \(x, y\) axes locate at the plane of the interface. We assume plane wave with frequency \(\omega\) incident from isotropic media into anisotropic media. In isotropic media the accompanying dispersion relation has the familiar form

\[
k_x^2 + k_y^2 + k_z^2 = \varepsilon_I \mu_I \frac{\omega^2}{c^2}.
\]

Here \(k_i\) is the \(i\) component of the propagating wave vector and \(c\) is the speed of light in vacuum. \(\varepsilon_I\) and \(\mu_I\) are the permittivity and permeability, respectively.

In the uniaxially anisotropic media, the E- and H- polarized incident waves have the
dispersion relation \[18, 22\]

\[
\frac{q_x^2}{\varepsilon_y \mu_z} + \frac{q_y^2}{\varepsilon_x \mu_z} + \frac{q_z^2}{\varepsilon_y \mu_x} - \frac{\omega^2}{c^2} = 0,
\]

(3)

\[
\frac{q_x^2}{\varepsilon_z \mu_y} + \frac{q_y^2}{\varepsilon_z \mu_x} + \frac{q_z^2}{\varepsilon_y \mu_x} - \frac{\omega^2}{c^2} = 0.
\]

(4)

Here \(q_i\) represents the \(i\) component of transmitted wave-vector. If the permittivity and permeability constants satisfy the relation:

\[
\frac{\varepsilon_x}{\mu_x} = \frac{\varepsilon_y}{\mu_y} = \frac{\varepsilon_z}{\mu_z} = C \quad (C < 0),
\]

(5)

where \(C\) is a constant, then the E- and H- polarized waves have the same dispersion relation \[18, 21\]

\[
\frac{q_x^2}{\varepsilon_z \mu_y} + \frac{q_y^2}{\varepsilon_z \mu_x} + \frac{q_z^2}{\varepsilon_y \mu_x} = \frac{\omega^2}{c^2},
\]

(6)

Based on the dispersion relation one can find that the wave-vector surface is a single-sheeted hyperboloid. It should be mentioned that the propagation character in quasiisotropic media \(C > 0\) has been discussed in our previous work. We have shown that E- and H- polarized waves have the same propagation character in quasiisotropic medium \[17\]. In present work, we want to enquire whether E- and H- polarized waves have the same propagation feature.

III. POSITIVE AND NEGATIVE REFRACTION

In this section, we shall answer the question asked in the above section. The z-component of the wave vector can be found by the solution of Eq. (6), which yields

\[
q_z = \sigma \sqrt{\frac{\varepsilon_y \mu_z}{c^2} \left( \frac{\varepsilon_y \mu_x}{\varepsilon_z \mu_y} q_x^2 + \frac{\varepsilon_y}{\varepsilon_z} q_y^2 \right)},
\]

(7)

where \(\sigma = +1\) or \(\sigma = -1\). The choice of the sign ensures that light power propagates away from the surface to the +z direction.

Without loss of generality, we assume the wave vector locate in the \(x - z\) plane \(k_y = q_y = 0\). The incident angle of light is given by

\[
\theta_I = \tan^{-1} \left[ \frac{k_x}{k_z} \right],
\]

(8)
FIG. 2: The circle and single-sheeted hyperbola represent the dispersion relations of the isotropic medium and the anisotropic medium, respectively. The incident wave vector \( \mathbf{k} \) is parallel to the Poynting vector \( \mathbf{S}_I \) in the isotropic medium. Because the anisotropy, \( \mathbf{S}_T \) must lie normal to the frequency contour. The single-sheeted hyperboloid wave-vector surface has two types: (a) \( \beta_E^P = \beta_H^P > 0, \beta_E^S = \beta_H^S < 0 \), (b) \( \beta_E^P = \beta_H^P < 0, \beta_E^S = \beta_H^S > 0 \).

In principle the occurrence of refraction requires that the \( z \) component of the wave vector of the refracted waves must be real. Then the incident angle must satisfy the following inequality:

\[
\frac{\varepsilon_y \mu_x}{\varepsilon_z \mu_y} q_x^2 > \varepsilon_y \mu_x \omega^2 c^2.
\]  

(9)

Based on the boundary condition, the tangential components of the wave vectors must be continuous

\[
q_x = k_x = \frac{\sqrt{\varepsilon_I \mu_I} \omega}{c} \sin \theta_I.
\]  

(10)

Substituting Eq. (10) into Eq. (9), one can obtain E- and H-polarized waves have the same critical angle

\[
\theta_C^E = \theta_C^H = \sin^{-1} \left( \sqrt{\frac{\varepsilon_z \mu_y}{\varepsilon_I \mu_I}} \right).
\]  

(11)

The refractive angle of the transmitted wave vector or phase of E- and H-polarized waves can be written as

\[
\beta_P^E = \tan^{-1} \left( \frac{q_x^E}{q_z^E} \right), \quad \beta_P^H = \tan^{-1} \left( \frac{q_x^H}{q_z^H} \right).
\]  

(12)

It should be noted that the actual direction of light is defined by the time-averaged Poynting vector \( \mathbf{S} = \frac{1}{2} \text{Re}(\mathbf{E}^* \times \mathbf{H}) \). For E- polarized incident waves, the Poynting vector is given by

\[
\mathbf{S}_T^E = \text{Re} \left[ \frac{E_0^2 q_x^E}{2 \omega \mu_z} \mathbf{e}_x + \frac{E_0^2 q_z^E}{2 \omega \mu_x} \mathbf{e}_z \right].
\]  

(13)
For H-polarized incident waves, the transmitted Poynting vector is given by

\[ S^H_T = \text{Re} \left[ \frac{H_x^0 q_x^H}{2\omega \varepsilon_z} e_x + \frac{H_z^0 q_z^H}{2\omega \varepsilon_x} e_z \right]. \]  

(14)

The refractive angle of Poynting vector of E- and H- polarized incident waves can be obtained as

\[ \beta^E_S = \tan^{-1} \left[ \frac{S_x^E}{S_z^E} \right], \quad \beta^H_S = \tan^{-1} \left[ \frac{S_x^H}{S_z^H} \right]. \]  

(15)

For the purpose of illustration, the frequency contour will be used to determine the refracted waves as shown in Fig. 2. From the boundary condition \( q_x = k_x \), we can obtain two possibilities for the refracted wave vector. Energy conservation requires that the z component of poynting vector must propagates away from the interface, for instance, \( q_z^E / \mu_x > 0 \) and \( q_z^H / \varepsilon_x > 0 \). Then the sign of \( q_z^E \) and \( q_z^H \) can be determined easily. The corresponding Poynting vector should be drawn perpendicularly to the dispersion contour. Thus we can obtain two possibilities (inward or outward), while only the Poynting vector with \( S_T z > 0 \) is causal.

As can be seen from Fig. 2, the wave-vector surface is a single-sheeted hyperbola. This medium has two types:

(I) For the case of \( \varepsilon_x > 0, \varepsilon_y > 0 \) and \( \varepsilon_z < 0 \), the refraction diagram is plotted in Fig. 2a. For E-polarized incident waves \( k_z \cdot q_z^E < 0, k_x \cdot S^E_T > 0 \). For H-polarized incident waves \( k_z \cdot q_z^H > 0, k_x \cdot S^H_T < 0 \). From Eqs. (13) and (14), if \( \varepsilon_x / \mu_x = \varepsilon_z / \mu_z = C < 0 \), \( S^E_T \) and \( S^H_T \) have the same sign, while \( S^E_T z \) and \( S^H_T x \) are always in the opposite sign, i.e.

\[ \beta^E_P = -\beta^H_P < 0, \quad \beta^E_S = -\beta^H_S > 0. \]  

(16)

(II) For the case of \( \varepsilon_x < 0, \varepsilon_y < 0 \) and \( \varepsilon_z > 0 \), the refraction diagram is plotted in Fig. 2b. For E-polarized incident waves \( k_z \cdot q_z^E > 0, k_x \cdot S^E_T < 0 \). For H-polarized incident waves \( k_z \cdot q_z^H < 0, k_x \cdot S^H_T > 0 \). From Eqs. (13) and (14) we can get

\[ \beta^E_P = -\beta^H_P > 0, \quad \beta^E_S = -\beta^H_S < 0. \]  

(17)

We thus conclude that E- and H-polarized waves have the same dispersion relation while E- (or H-) polarized beam is positively refracted whereas H- (or E-) polarized beam is negatively refracted in such anisotropic media.

In following analysis we are interested in type I, in which the E-polarized waves are positively refracted whereas the H-polarized waves are negatively refracted. The refractive
The variations of the refractive angle $\beta_S$ for energy flow and the transmitted wave vector angle $\beta_P$ as a function of the incident angle $\theta_I$. The E-polarized beam undergoes a positive refraction, while the energy flow of H-polarized beam undergoes negative refraction.

angles of Poynting vector and wave vector are plotted in Fig. 3. For the purpose of illustration, We choose some simple anisotropic parameters, i.e. $\varepsilon_x = 2$, $\varepsilon_y = 1$, $\varepsilon_z = 0.5$ and $C = -1$. It should be mentioned that the parameters can be effectively modelled in periodic wires and rings structure [14, 15].

The above analysis suggest that a large splitting angle can be obtained by tuning the anisotropic parameters. The splitting angle between E- and H-polarized waves can be defined as

$$\Phi = \beta_E^S - \beta_H^S. \quad (18)$$

If the waves incident at $\theta = 60^\circ$, the splitting angle will reach a large value $\Phi = 148^\circ$ as shown in Fig. 3. A question naturally arise: why do we not use the special medium to construct an efficient splitter?

**IV. WAVES INCIDENT AT BREWSTER ANGLE**

From the analysis of the previous section we know that E-polarized beam is positively refracted whereas H-polarized beam is negatively refracted by the anisotropic slab. The interesting properties allow us to introduce the potential device acting as a polarizing beam
The optical beam splitter consists of an anisotropic medium slab as shown in Fig. 4. The media parameters of anisotropic slab can be tuned to meet the requirements, for example, the reflection coefficient of a E-polarized wave equals to that of a H-polarized wave. Based on the boundary conditions, the reflection and the transmission coefficients can be obtained \[21\]. For E-polarized incident waves, one can obtain the following expression for the reflection and transmission coefficients

\[ R_E = \frac{\mu_x k_z - \mu_I q_z^E}{\mu_x k_z + \mu_I q_z^E}, \quad T_E = \frac{2\mu_x k_z}{\mu_x k_z + \mu_I q_z^E}. \]  \hspace{1cm} (19)

For H-polarized incident waves, the reflection and transmission coefficients can be obtained similarly as

\[ R_H = \frac{\varepsilon_x k_z - \varepsilon_I q_z^H}{\varepsilon_x k_z + \varepsilon_I q_z^H}, \quad T_H = \frac{2\varepsilon_x k_z}{\varepsilon_x k_z + \varepsilon_I q_z^H}. \]  \hspace{1cm} (20)

Mathematically the Brewster angles can be obtained from \( T_E = 0 \) and \( T_H = 0 \). For E-polarized incident waves if the anisotropic parameters satisfy the relation

\[ 0 < \frac{\mu_z(\varepsilon_y \mu_1 - \varepsilon_1 \mu_x)}{\varepsilon_1 (\mu_1^2 - \mu_x \mu_z)} < 1, \]  \hspace{1cm} (21)

the Brewster angle can be expressed as

\[ \theta_{EB}^E = \sin^{-1} \left[ \sqrt{\frac{\mu_z(\varepsilon_y \mu_1 - \varepsilon_1 \mu_x)}{\varepsilon_1 (\mu_1^2 - \mu_x \mu_z)}} \right]. \]  \hspace{1cm} (22)

For H-polarized waves if the anisotropic parameters satisfy by the relation

\[ 0 < \frac{\varepsilon_z(\varepsilon_I \mu_y - \varepsilon_x \mu_1)}{\mu_1(\varepsilon_1^2 - \varepsilon_x \varepsilon_z)} < 1, \]  \hspace{1cm} (23)

FIG. 4: Schematic diagram illustrating the polarized beams splitter
FIG. 5: The reflection coefficients of E- and H-polarized waves as functions of the incident angle \( \theta_I \). E- and H-polarized waves exhibit a Brewster angle simultaneously: (a) \( \theta_E^B \neq \theta_H^B \), (b) \( \theta_E^B = \theta_H^B \).

The Brewster angle can be written in the form

\[
\theta_H^B = \sin^{-1} \left[ \frac{\varepsilon_z (\varepsilon_I \mu_y - \varepsilon_x \mu_I)}{\mu_I (\varepsilon_y^2 - \varepsilon_x \varepsilon_z)} \right].
\]  

(24)

It should be mentioned that E- and H-polarized waves may exhibit a Brewster angle simultaneously, which depends on the choice of the anisotropic parameters. Clearly, if one seeks a solution satisfying Eq. (22) and Eq. (24), the only possibility is

\[
\frac{\varepsilon_x}{\mu_x} = \frac{\varepsilon_y}{\mu_y} = \frac{\varepsilon_z}{\mu_z} = -\frac{\varepsilon_I}{\mu_I},
\]  

(25)

one can obtain an interesting features: E- and H-polarized waves will exhibit the same reflection and transmission, namely, \( R_E = R_H \) and \( T_E = T_H \).

The reflection coefficients of E- and H-polarized waves are plotted in Fig. 5. We choose some simple parameters for the purpose of illustration, i.e., \( C = -1 \). In Fig. 5a E- and H-polarized incident waves exhibit a Brewster angle, simultaneously. When the incident angle equal to the Brewster angle, the incident waves will exhibit oblique total transmission. In Fig. 5b E- and H-polarized waves exhibit the same Brewster angle. We can find E- and H-polarized waves will exhibit oblique total transmission at same indigent angle.

To construct an efficient splitter, we wish that E- and H-polarized waves can totally transmit thought the anisotropic slab. We thus choose the incident angle equal to the Brewster angle \( \theta_I = \theta_E^B = \theta_H^B \), the reflects of E- and H-polarized waves are completely absent.
V. POLARIZING BEAM SPLITTER BASED ON THE ANOMALOUS REFRACTION

The splitting distance (or walk-off distance) between E- and H-polarized beam is the function of anisotropic parameters, the incident angle and the slab thickness. The splitting distance can be easily obtained as

\[
d = 2 \cos \theta_I \tan \beta_S l,
\]

where \(d\) is the splitting distance and \(l\) is the thickness of slab.

To obtain a better physical picture of beam splitter, a modulated Gaussian beam of finite width can be constructed. Following the method outlined by Lu et al. \[24\], let us consider a modulated beam incident from free space

\[
E_1(x, z) = \int_{-\infty}^{+\infty} dk_\perp f(k_\perp) \exp[i(k_0 + k_\perp) \cdot r - i\omega_0 t],
\]

where \(k_\perp\) is perpendicular to \(k_0\) and \(\omega_0 = c k_0\). A general incident wave vector is written as \(k = k_0 + k_\perp\). we assume its Gaussian weight is

\[
f(k_\perp) = \frac{w_0}{\sqrt{\pi}} \exp[-w_0^2 k_\perp],
\]

where \(w_0\) is the spatial extent of the incident beam. We want the modulated Gaussian beam to be aligned with the incident direction defined by the vector \(k_0 = k_0 \cos \theta_I e_x + k_0 \sin \theta_I e_z\), which makes the incident angle equal to the Brewster angle.

Matching the boundary conditions for each \(k\) component at \(z = 0\) gives the complex field in the form

\[
E_2(x, z) = \int_{-\infty}^{+\infty} dk_\perp f(k_\perp) T_1(k) \exp[i(q \cdot r - \omega_0 t)].
\]

where \(T_1(k)\) is the transmission coefficient of the modulated Gaussian beam at the first interface. The transmission coefficient can obtain a good approximation to simply evaluate this quantity at \(k_0\). We set the waves are incident at the Brewster angle, then the transmission coefficient of the modulated beam is simply given by \(T_1(k_0) = 1\). The normal component of refracted wave vector \(q_z\) can be expanded in a Taylor series to first order in \(k_0\) to obtain a better approximation

\[
q_z^E(k) = q_z^E(k_0) + (k - k_0) \cdot \frac{\partial q_z^E(k)}{\partial k} \bigg|_{k_0}.
\]
FIG. 6: Observed polarization-splitting characteristics and their intensity distributions. (a) E-polarized beam is positively refracted, (b) H-polarized beam is negatively refracted. The anisotropic parameters are same as those used in Fig. 2. The splitting distance between the two beam peaks is $17.3w_0$.

\[ q_z^H(k) = q_z^H(k_0) + (k - k_0) \cdot \frac{\partial q_z^H(k)}{\partial k} \bigg|_{k_0}. \]  

(31)

The complex field in region 3 can be obtained similarly

\[ E_3(x, z) = \int_{-\infty}^{+\infty} dk_{\perp} f(k_{\perp})T_2(k) \exp[i(k_0 + k_{\perp}) \cdot r - i\omega_0 t]. \]  

(32)

where $T_2(k)$ is the transmission coefficient of the modulated Gaussian beam at the second interface. E- and H-polarized waves can totally propagate through the interface.

To this end, the intensity distribution of the transmission field in the free space and anisotropic media slab can be derived from Eqs. (27), (29) and (32) under the above approximation. For simplicity, the isotropic medium is assumed to be a vacuum in our calculation. Note that the refraction angles of energy of E- and H-polarized beams in the anisotropic medium slab are almost exactly the analytical expression in Eq. (18). Our numerical results indicate that it is advantageous to employ the anisotropic media slab as polarization beam splitter.

Finally we want to enquire: how can the beam splitting effect be studied experimentally? Generally speaking, it is not strange to mention the question because no scheme can be of much interest if the means of realizing it are not available. Fortunately several recent developments make the beam splitter a practical possibility. An extremely promising material has been previously explored in certain designs of photonic crystals, which can
be effectively modelled with anisotropic permittivity and permeability tensors \[25, 26, 27\]. Therefore there is no physical and technical obstacle to construct the anisotropic medium slab to split polarized beams.

VI. CONCLUSION

In conclusion, we have investigated the wave propagation in the anisotropic media with single-sheeted hyperboloid dispersion relation. In such anisotropic media E- and H-polarized waves have the same dispersion relation while E- (or H-) polarized beam is positively refracted whereas H- (or E-) polarized beam is negatively refracted. By suitably using propagation properties in such kind of anisotropic medium, it is possible to realize very simple and very efficient beam splitter. We show that the splitting distance between E- and H-polarized beam is the functions of anisotropic parameters, the incident angle and the slab thickness. We are sure that our scheme has not exhausted the interesting possibilities. In particular, it might be imagined that a series of beam splitter could be constructed in more sophisticated processes than those considered here.

Acknowledgments

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