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Total reflection of electromagnetic waves propagating from an isotropic medium to an indefinite metamaterial

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Abstract

The existence conditions for total reflection and the corresponding critical angle at the interface separating an isotropic medium and an indefinite metamaterial for TE- and TM-polarized electromagnetic waves are obtained. For different kinds of indefinite metamaterial, there appear different total reflection phenomena. Particularly, the anomalous total reflection in which the incident angle is smaller than the critical angle and the Brewster's angle can be smaller than the critical angle can occur for anti-cutoff medium. Furthermore, the omni-directional total reflection exists for the always cutoff medium and anti-cutoff medium. The total reflection depends on the thickness of indefinite metamaterial when the indefinite metamaterial is finite, and the photon tunneling phenomenon can occur when the thickness of indefinite metamaterial is smaller than wavelength.

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Keywords: Indefinite medium; Negative index material; Total reflection; Photon tunneling

1. Introduction

The negative index material (NIM) with negative permittivity and negative permeability simultaneously, first introduced by Veselago [1], has recently received much attention in the literatures owing to its very unusual properties [2–5], such as negative refraction index [5] and wave vector antiparallel to the Poynting vector [1]. NIMs were realized primarily in the microwave range. Nowadays, NIMs in the near IR and optical range have also been experimentally demonstrated [6,7]. Several applications have been envisioned for these materials: perfect lens [3], compact-cavity resonators [8], phase shifters [9], and efficient waveguide [10,11]. Recently, the characteristics of electromagnetic waves propagation in anisotropic NIM, even an indefinite metamaterial [12] in which not all the principal elements of the permeability and permittivity tensors have the same sign also have been discussed extensively. Schurig and Smith have outlined a potentially useful application of the indefinite metamaterial as a spatial filtering [13]. Hu and Chui have mainly discussed under what conditions anomalous reflection or refraction can occur at the interface when propagating waves pass from one isotropic regular medium into another uniaxially anisotropic NIM medium [14]. Furthermore, Shen and Wang predicted the existence of a total transmission phenomenon at the interface separating a regular material and an indefinite metamaterial under suitable conditions [15].

In classical electromagnetic field theory, when light travels from the optically dense material to the optically rarer material, the total reflection will occur if the incident angle is larger than the critical angle [16]. This phenomenon has been found applications in attenuated total reflection spectroscopy [17], scanning photon tunneling microscopy [18], and microscale thermophotovoltaic devices [19]. In this paper, we investigate the problem of total reflection of

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electromagnetic waves at the interface formed by an isotropic regular material and an indefinite metamaterial. We present a detailed analysis on the existence conditions for total reflection for all the possible physical parameters. This total reflection phenomenon is significantly different from that for isotropic materials. This paper is organized as following. We first investigate the propagation characteristic at the interface between an isotropic medium and an indefinite metamaterial in Section 2. Then we discuss the existence conditions for the total reflection and the critical angle when the light goes from the isotropic medium to the indefinite metamaterial in Section 3. In Section 4, we analyze the condition for total reflection when the indefinite metamaterial is finite, and present a numerical result. Finally, in Section 5, we give our conclusion.

2. Propagation characteristics of electromagnetic wave at the interface with indefinite metamaterial

The geometry of the considered problem is shown in Fig. 1, where the plane wave of angular frequency ω is incident from the medium 1 at an incident angle θ into the medium 2 (indefinite metamaterial). The medium 1 is characterized by the permittivity ε_1 and the permeability μ_1, and the indefinite metamaterial is characterized by the permittivity ε, the permeability μ. The interface of the two media is parallel to the xy plane, and the normal direction is the z-axis. To simplify the proceeding analysis, we assume the anisotropic permittivity and permeability tensors can be simultaneously diagonalizable, then ε and μ tensors can be denoted as the following forms:

$$\varepsilon = \begin{pmatrix} \varepsilon_x & 0 & 0 \\ 0 & \varepsilon_y & 0 \\ 0 & 0 & \varepsilon_z \end{pmatrix}, \quad \mu = \begin{pmatrix} \mu_x & 0 & 0 \\ 0 & \mu_y & 0 \\ 0 & 0 & \mu_z \end{pmatrix}. \tag{1}$$

In the subsequent analysis, we assume that the indefinite metamaterial is optically uniaxial, and the optical axis (z-axis) is normal to the interface, then $\varepsilon_x = \varepsilon_y \neq \varepsilon_z$ and $\mu_x = \mu_y \neq \mu_z$.

Without loss of generality, we assume that the wave vector locates at the xz plane, and the incident electric field is $E = \hat{y}E_0 e^{i(k_x x + k_{1z} z - \omega t)}$, where k_x and k_{1z} are x and z components of the incident wave vector. We first discuss the TE modes, and the TM modes can be treated similarly. For the TE waves, the dispersion relation in the isotropic regular medium is

$$k_x^2 + k_{1z}^2 = \varepsilon_1 \mu_1 (\omega^2/c^2), \tag{2}$$

and for the indefinite metamaterial, it is

$$\frac{k_x^2}{\varepsilon_y \mu_z} + \frac{k_{2z}^2}{\varepsilon_y \mu_x} = \frac{\omega^2}{c^2}. \tag{3}$$

Thus the normal wave vector component in the indefinite metamaterial satisfies,

$$k_{2z}^2 = (\omega^2/c^2)[\varepsilon_y \mu_x - (\mu_x/\mu_z)\varepsilon_1 \mu_1 \sin^2\theta]. \tag{4}$$

In the absence of loss, the sign of k_{2z}^2 can be used to distinguish the nature of the plane-wave solutions. $k_{2z}^2 > 0$ corresponds to real valued k_{2z} and propagating solutions. $k_{2z}^2 < 0$ corresponds to imaginary valued k_{2z} and exponentially growing or decaying (evanescent) solutions. It is noted that the sign of the wave vector k_{2z} must ensure the Poynting vector inside the indefinite metamaterial to point away from the interface between the incident and indefinite metamaterial, and according to reference [20], k_{2z} and μ_x must keep the same sign.

The reflection coefficients and transmission coefficients can be found by considering the boundary conditions for the electric field and magnetic field at the interface

$$r^{TE} = \frac{\mu_x k_{1z} - \mu_1 k_{2z}}{\mu_x k_{1z} + \mu_1 k_{2z}}, \tag{5}$$

$$t^{TE} = \frac{2\mu_x k_{1z}}{\mu_x k_{1z} + \mu_1 k_{2z}}. \tag{6}$$

Similarly, we also easily obtain the reflection coefficients and transmission coefficients for TM waves:

$$r^{TM} = \frac{\varepsilon_x k_{1z} - \varepsilon_1 k'_{2z}}{\varepsilon_x k_{1z} + \varepsilon_1 k'_{2z}}, \tag{7}$$

$$t^{TM} = \frac{2\varepsilon_x k_{1z}}{\varepsilon_x k_{1z} + \varepsilon_1 k'_{2z}}, \tag{8}$$

where

$$k'^2_{2z} = (\omega^2/c^2)[\varepsilon_x \mu_y - (\varepsilon_x/\varepsilon_z)\varepsilon_1 \mu_1 \sin^2\theta]. \tag{9}$$

If the optical axis of the indefinite metamaterial is parallel to the interface between the two media, we can also choose the z-axis to be normal to the interface and the x-axis to be along the optical axis, then $\varepsilon_x \neq \varepsilon_y = \varepsilon_z$ and $\mu_x \neq \mu_y = \mu_z$. Finally the reflection coefficient and transmission coefficient can be obtained similarly.

It is easily found from Eqs. (5)–(9) that the total reflection occurs when

$$R^{TE} = |r^{TE}|^2 = 1 \tag{10}$$

for TE waves and when

$$R^{TM} = |r^{TM}|^2 = 1 \tag{11}$$

for TM waves. In the conventional medium, at the interface formed by two regular media, when the incident angle

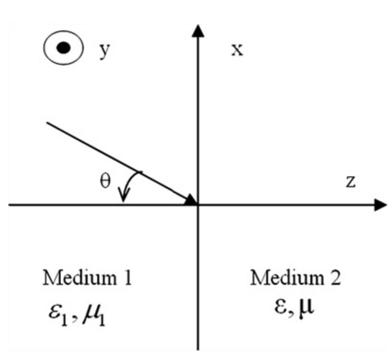

Fig. 1. Geometrical structure of the problems. The optical axis of the indefinite metamaterial is z-axis.