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Light transmission along a slab waveguide with a core of anisotropic metamaterial

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Abstract

We investigated the dispersion property of a slab waveguide with an anisotropic metamaterial core whose permittivity tensor is partially negative. The subwavelength guidance characteristics are presented based on the boundary conditions. The results show that, at some specific frequencies, many high-order modes can exist in present waveguide even with the thickness of the guiding core 10 times smaller than the working wavelength. It is also found that different orientations of the optical axis of the anisotropic core will lead to different dispersion of the guided modes. If the orientation of the optical axis is properly chosen, the guided modes show a transition from backward wave to a forward wave as the frequency increases. During this transition, the group velocity of some guided modes can approach zero. Since the anisotropic metamaterial we discuss here can be fabricated in GHz, near- and mid-infrared frequencies, our result may find some applications in wave trapper, integrated optical and nanophotonic devices.

Keywords: Anisotropic metamaterial; Subwavelength guidance; Slow propagation; Wave trapper

1. Introduction

The metamaterial also known as left-handed material [1] has attracted much attention after the first experimental realization at some microwave frequencies [2]. The novel material exhibits simultaneously negative electric permittivity and magnetic permeability values and thus possesses a negative refraction index, as Veselago [1] first predicted theoretically in 1968. Based on the novel property of metamaterial, many ideas and potential applications have been proposed [3–8]. The study of the properties in metamaterial waveguides is a large new area, which can be extended to useful applications [6,7]. For conventional waveguides based on total internal reflection, the guiding layers can theoretically be scaled down as much as possible by increasing the difference between the refraction index of the guiding core and its claddings. However, two limitations are associated with the high refraction index guiding core. First, large propagating constant in high refraction index core makes it difficult to couple the wave into the guiding core. Second, one will eventually meet the difficulty on obtaining high refraction index material. For the conventional symmetrical waveguide, there are no cut-off frequencies for the fundamental modes, therefore the size of the guiding core can go to zero theoretically. However, the field confinement is poor for the fundamental modes and the waveguide will

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suffer from large scattering losses while reducing the thickness of the guiding core [9].

In this paper, we investigate the dispersion property of the guided modes in a subwavelength slab waveguide with an anisotropic metamaterial core whose permittivity tensor is partially negative [8]. The result shows that, at some specific frequencies, many high-order modes can exist in present waveguide even with the thickness of the guiding core 10 times smaller than the working wavelength. Therefore, it is possible to scale down the waveguide to subwavelength size and the field confinement of the high-order modes can be much better than the fundamental modes [10]. It is also found that different orientations of the optical axis of the anisotropic metamaterial core will lead to different dispersions of the guided modes. If the orientation of the optical axis is properly chosen, the guided modes show a transition from the backward wave to the forward wave as the frequency increases. During this transition, the group velocity of some guided modes can approach zero. Since the anisotropic metamaterial we discuss here can be fabricated in GHz, near- and mid-infra-red frequencies [11,12], our result may have some applications in wave trapper, integrated optical and nanophotonics device.

2. Determination of the guided modes

We first consider an electrically uniaxial media with a scalar permeability $\mu = 1$ and a permittivity tensor

$$\bar{\bar{\varepsilon}} = \begin{pmatrix} \varepsilon_1 & 0 & 0 \\ 0 & \varepsilon_1 & 0 \\ 0 & 0 & \varepsilon_2 \end{pmatrix}, \tag{1}$$

which is given in the principle coordinates (x–y–z system). The optical axis is along z-direction with dielectric constant ε_2. For a conventional uniaxial media, ε_1 and ε_2 are both positive. However, ε_2 can be negative and obey the frequency dependence of the well-known Drude model (note that ε_1 is still a positive constant). In GHz frequencies, the idea to achieve $\varepsilon_2 < 0$ can be realized in a composite of periodically arranged metallic thin wires aligned along the optical axis [13,14], and in optical, near- and mid-infrared frequencies, it can be, respectively, achieved by various techniques described in Ref. [11]. As an example, for the composite of 10% of SiC nano-spheroids with an aspect ratio of 1/2, aligned with their shorter axis along the optical axis and embedded in quartz, we can obtain $\varepsilon_2 = -2.7 + 6 \times 10^{-4} i$, $\varepsilon_1 = 1.6 + 1 \times 10^{-5} i$ for a wavelength of CO_2 laser of 12 μm.

A slab waveguide with a partially negative permittivity core is shown in Fig. 1. The thickness of the core is d and the cladding layers are air. The angle between the

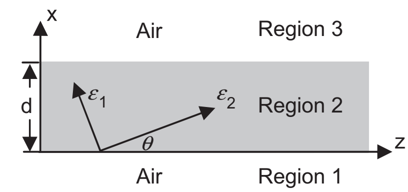

Fig. 1. Slab waveguide with $\varepsilon_1 > 0$ and $\varepsilon_2 < 0$.

optical axis and the z-axis is θ (note that the optical axis is in the x–z plane).

Consider a TM incidence wave with the magnetic field polarized along y-axis. In order to guide the fields in the core, the fields in the claddings must be evanescent along the x direction. We write the magnetic fields in regions 1–3 as

$$\vec{H}_1 = \vec{y}\, A_1 e^{\alpha x} e^{i k_z z}, \quad x < 0, \tag{2a}$$

$$\vec{H}_2 = \vec{y} \left[A_2 e^{i k_{2x}^i x} + B_2 e^{i k_{2x}^r x} \right] e^{i k_z z}, \quad 0 \leqslant x \leqslant d, \tag{2b}$$

$$\vec{H}_3 = \vec{y}\, A_3 e^{-\alpha x} e^{i k_z z}, \quad x > d, \tag{2c}$$

respectively, where α represents the attenuation factor. Based on Ampere's law, the electric displacement D is

$$D_{1x} = \frac{k_z}{\omega} A_1 e^{\alpha x} e^{i k_z z}, D_{1z} = -\frac{\alpha}{\omega i} A_1 e^{\alpha x} e^{i k_z z}, \tag{3a}$$

$$\begin{aligned} D_{2x} &= \frac{k_z}{\omega} \left(A_2 e^{i k_{2x}^i x} + B_2 e^{i k_{2x}^r x} \right) e^{i k_z z}, \\ D_{2z} &= -\frac{1}{\omega} \left(A_2 k_{2x}^i e^{i k_{2x}^i x} + B_2 k_{2x}^r e^{i k_{2x}^r x} \right) e^{i k_z z}, \end{aligned} \tag{3b}$$

$$D_{3x} = \frac{k_z}{\omega} A_3 e^{-\alpha x} e^{i k_z z}, \quad D_{3z} = \frac{\alpha}{\omega i} A_3 e^{-\alpha x} e^{i k_z z}. \tag{3c}$$

The dispersion relations of the claddings and the core are

$$k_z^2 - \alpha^2 = (\omega / c)^2, \tag{4a}$$

$$\begin{aligned} & k_{2x}^2 (\varepsilon_1 \cos^2\theta + \varepsilon_2 \sin^2\theta) + k_z^2 (\varepsilon_2 \cos^2\theta + \varepsilon_1 \sin^2\theta) \\ & \quad + 2 \sin\theta \cos\theta k_{2x} k_z (\varepsilon_2 - \varepsilon_1) - \varepsilon_2 \varepsilon_1 (\omega / c)^2 = 0, \end{aligned} \tag{4b}$$

respectively, where c is the speed of light in the air, and k_{2x}^i, k_{2x}^r are the solutions of Eq. (4b) for a given k_z. The permittivity tensor of the core can be expressed as

$$\bar{\bar{\varepsilon}} = \begin{pmatrix} \varepsilon_1 \cos^2\theta + \varepsilon_2 \sin^2\theta & 0 & -\sin\theta \cos\theta (\varepsilon_1 - \varepsilon_2) \\ 0 & \varepsilon_1 & 0 \\ -\sin\theta \cos\theta (\varepsilon_1 - \varepsilon_2) & 0 & \varepsilon_1 \sin^2\theta + \varepsilon_2 \cos^2\theta \end{pmatrix}. \tag{5}$$

Applying $\overline{D} = \bar{\bar{\varepsilon}} \cdot \overline{E}$, we get the z component of E-field as

$$E_{2z} = D_{2x} \sin\theta \cos\theta \left(\frac{1}{\varepsilon_2} - \frac{1}{\varepsilon_1} \right) + D_{2z} \left(\frac{\cos^2\theta}{\varepsilon_2} + \frac{\sin^2\theta}{\varepsilon_1} \right). \tag{6}$$