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Investigation of uniaxial anisotropic chiral metamaterial waveguide with perfect electromagnetic conductor loading

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ABSTRACT

The paper presents investigations of the electromagnetic characteristics of circular waveguides made of uniaxial anisotropic chiral medium; the outer surface of the guide being coated with a PEMC (perfect electromagnetic conductor) medium. The emphasis is given on the energy flux density patterns of such guides with varieties of anisotropic chiral materials. Dispersion relation of the guide is developed, and followed by the evaluation of sustained modes, which determine the energy flux density patterns corresponding to different low-order hybrid modes. The flux density characteristics provide the evidence of existing backward waves in uniaxial anisotropic mediums, contributing more to the phenomenon of *slow light* in chiral metamaterials.

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1. Introduction

Electromagnetic properties of a material can be described by the electric permittivity and the magnetic permeability values, which microscopically determine the effects due to the induced electric and magnetic fields [1]. Extensive studies have been reported on tailored composite structures to attain specific electromagnetic properties. Within the context, the development of microstructured materials, that can effectively provide simultaneously negative values of permittivity and permeability over a finite frequency range, have been of great interest. These materials essentially exhibit negative refractive index [2].

Negatively refracting materials are of much technological need owing to their having many fabulous characteristics and applications, especially in nanotechnology [3–5]. These are also called as left-handed or double negative (DNG) materials owing their simultaneous negative values of permittivity and permeability. After the idea of negative index materials put forward [2], DNG materials were proposed with the conceptual understanding in designing split ring resonators, conducting wires, loops and tubes of conductors with inserted gaps [6]. Negative index metamaterials gain exotic properties due to structures rather than compositions [7].

Chiral metamaterials have been greatly interesting as these too owe the phenomena of negative reflection and/or refraction through suitably controlling the chirality (coupling) parameter. These possess the properties of circular dichroism [8] and strong optical activity [9], and essentially have advantages over DNG materials as these are easy to design and have more bandwidth.

In uniaxial anisotropic chiral metamaterials, chirality remains unidirectional. These are easy to fabricate by placing miniature spiral or conducting springs in the host dielectric medium [10,11]. Electromagnetic wave propagation through waveguides comprised of chiral, uniaxial chiral and chiral nihility metamaterials have been appeared in the literature [10–17]. Apart from these, the scattering behavior of electromagnetic waves from PEMC based mediums has been reported [18].

In this context, it is worth to state that the concept of PEMC was proposed by Lindell and Sihvola [19], and the boundary conditions in the case of PEMC medium are defined as

$$\hat{n} \times (\vec{H} + M\vec{E}) = 0$$

where M represents a real scalar admittance. Also, PEMC is a generalized case of perfect electric conductor (PEC) and perfect magnetic conductor (PMC) mediums. The cases $M \to \infty$ and $M \to 0$, respectively, determine the situations corresponding to PEC and PMC mediums.

In the present communication, efforts are put to explore the propagation behavior of electromagnetic energy flux density through a cylindrical waveguide with circular cross-section and made of uniaxial anisotropic chiral metamaterial; the outer surface of guide being coated with a PEMC medium. The nature of energy flux density patterns corresponding to the propagating hybrid modes is studied taking into account varieties of chiral structures. Investigations reveal that, for most of the propagating hybrid

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modes, the flux density remains more confined near the central region of the guide, and the flux patterns greatly vary by varying the type of chiral metamaterial in use. Furthermore, both the forward and the backward wave propagations exist in the guide – the latter one being as partially contributing to slow light propagation.

2. Theory

We consider a circular waveguide as shown in Fig. 1. The core section of guide is made of homogeneous and lossless uniaxial anisotropic chiral metamaterial with the radial parameter a, and loaded with a PEMC medium. Thus, the region with $r \le a$ is comprised of chiral medium, and that with $r > a$ is the PEMC medium. The constitutive relations corresponding to uniaxial anisotropic chiral mediums are prescribed as [20]

$$\vec{D} = [\varepsilon_t \bar{\bar{I}}_t + \varepsilon_z \hat{u}_z \hat{u}_z] \cdot \vec{E} - j\kappa(\varepsilon_0\mu_0)^{\frac{1}{2}} \hat{u}_z \hat{u}_z \cdot \vec{H} \tag{1a}$$

$$\vec{B} = [\mu_t \bar{\bar{I}}_t + \mu_z \hat{u}_z \hat{u}_z] \cdot \vec{H} - j\kappa(\varepsilon_0\mu_0)^{\frac{1}{2}} \hat{u}_z \hat{u}_z \cdot \vec{E} \tag{1b}$$

In these equations, $\hat{u}_z$ is the unit vector along the optical axis of guide, κ is the chirality parameter, ε_z and μ_z are, respectively, permittivity and permeability of the medium along the longitudinal axis of guide, and ε_t and μ_t are those along the transverse direction. Furthermore, $\bar{\bar{I}}_t$ is the unit dyadic defined as

$$\bar{\bar{I}}_t = \hat{x}\hat{x} + \hat{y}\hat{y}.$$

Considering the harmonic form of the longitudinal component of the excited electric field as comprised of Bessel function, one may write the decomposed form of the excited field in the chiral medium as

$$e_{+z} = A_n J_n(k_+ r)\exp(jn\phi) \tag{2a}$$

$$e_{-z} = B_n J_n(k_- r)\exp(jn\phi) \tag{2b}$$

where ϕ represents the azimuthal coordinate, k is the wave vector and $J_n(\cdot)$ is Bessel function of order n. Also, A_n and B_n are unknown coefficients to be determined by the boundary conditions. Thus, the total electromagnetic field inside the chiral medium will be represented by the sum

$$e = e_+ + e_- \tag{3a}$$

$$h = \frac{j}{\eta}(e_+ + e_-) \tag{3b}$$

with η as the impedance of chiral medium; e and h being the electric and the magnetic fields, respectively. Now, the electromagnetic fields can be decomposed into transverse and longitudinal components as

$$e = (e_t + \hat{z}e_z)\exp(-j\beta z) \tag{4a}$$

$$h = (h_t + \hat{z}h_z)\exp(-j\beta z) \tag{4b}$$

where β is the propagation constant in the medium. Upon using Maxwell's field equations, it can be shown that the total longitudinal components of electromagnetic fields will assume the forms as

$$e_{z1} = [A_n J_n(k_+ r) + B_n J_n(k_- r)]\exp[j(n\phi - \beta z)] \tag{5a}$$

and

$$h_{z1} = \frac{j}{\eta_t}[A_n\alpha_+ J_n(k_+ r) + B_n\alpha_- J_n(k_- r)]\exp[j(n\phi - \beta z)] \tag{5b}$$

Now, the total transverse components of the electromagnetic field, as derived by the use of Maxwell's equations and the longitudinal field components, can be given as

$$e_{r1} = \left[A_n\left\{\frac{jnk_t}{\lambda^2 r}\alpha_+ J_n(k_+ r) - \frac{j\beta k_+}{\lambda^2}J_n'(k_+ r)\right\} + B_n\left\{\frac{jnk_t}{\lambda^2 r}\alpha_- J_n(k_- r) - \frac{j\beta k_-}{\lambda^2}J_n'(k_- r)\right\}\right]\exp[j(n\phi - \beta z)] \tag{6a}$$

$$h_{r1} = \left[A_n\frac{1}{\lambda^2\eta_t}\left\{-\frac{nk_t}{r}J_n(k_+ r) + \beta k_+\alpha_+ J_n'(k_+ r)\right\} + B_n\frac{1}{\lambda^2\eta_t}\left\{-\frac{nk_t}{r}J_n(k_- r) + \beta k_-\alpha_- J_n'(k_- r)\right\}\right]\exp[j(n\phi - \beta z)] \tag{6b}$$

$$e_{\phi 1} = \left[A_n\left\{\frac{n\beta}{\lambda^2 r}J_n(k_+ r) - \frac{k_t\alpha_+ k_+}{\lambda^2}J_n'(k_+ r)\right\} + B_n\left\{\frac{n\beta}{\lambda^2 r}J_n(k_- r) - \frac{k_t\alpha_- k_-}{\lambda^2}J_n'(k_- r)\right\}\right]\exp\left[j(n\phi - \beta z)\right] \tag{7a}$$

$$h_{\phi 1} = \left[A_n\frac{1}{\lambda^2\eta_t}\left\{\frac{j\beta n\alpha_+}{r}J_n(k_+ r) - k_+ k_t J_n'(k_+ r)\right\} + B_n\frac{1}{\lambda^2\eta_t}\left\{\frac{j\beta n\alpha_-}{r}J_n(k_- r) - k_- k_t J_n'(k_- r)\right\}\right]\exp[j(n\phi - \beta z)] \tag{7b}$$

In these equations, prime represents the differentiation with respect to the argument, and $k_t = \omega\sqrt{\varepsilon_t\mu_t}$. Further

$$k_\pm^2 = \frac{\lambda^2}{2}\left[\frac{\varepsilon_z}{\varepsilon_t} + \frac{\mu_z}{\mu_t} \pm \sqrt{\left(\frac{\varepsilon_z}{\varepsilon_t} - \frac{\mu_z}{\mu_t}\right)^2 + 4\kappa^2\frac{\varepsilon_0\mu_0}{\varepsilon_t\mu_t}}\right] \tag{8}$$

Now, the eigenfunctions will be given as

$$(e_z, h_z) = \left(e_z, j\frac{\alpha}{\eta_t}e_z\right) \tag{9}$$

with $\alpha = \left(\frac{k^2}{\lambda^2} - \frac{\varepsilon_z}{\varepsilon_t}\right)\sqrt{\varepsilon_t\mu_t}/(k\sqrt{\varepsilon_0\mu_0})$ $\lambda^2 = \omega^2\mu_t\varepsilon_t - \beta^2$

and $\eta_t = \sqrt{\mu_t/\varepsilon_t}$

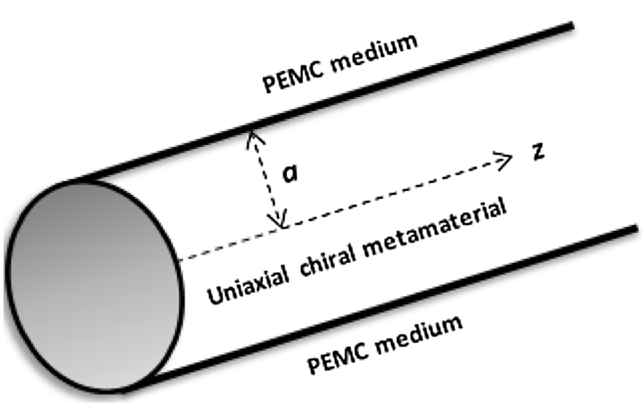

Fig. 1. Circular waveguide made of anisotropic chiral metamaterial with a PEMC boundary.

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