Optics Communications 403 (2017) 170–174

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Excitation of higher order modes in total transmission by zero index metamaterials with embedded defects

Roghayyeh Vahedpour [a], Mahdi Zavvari [b,*]

[a] Department of Electrical Engineering, Urmia branch, Islamic Azad University, Urmia, Iran
[b] Young Researchers and Elite Club, Urmia branch, Islamic Azad University, Urmia, Iran

ARTICLE INFO

Keywords:
Zero index metamaterial
Total transmission
Waveguide
Defect

ABSTRACT

A zero index metamaterial can be applied to perfect transmission or perfect reflection. In this paper we theoretically present a strategy of microwave transmission through a zero-index metamaterial waveguide loaded with defects. By simply adjusting the geometric and electromagnetic properties of the defects, higher modes can be excited in the total transmission or total reflection. To do so, a waveguide with two and three defects is considered and studied and the properties of defects are calculated from an analytical procedure. The results show excitation of higher modes in total transmission and reflection of waveguide.

1. Introduction

In recent years, there has been a considerable attention in the field of the artificially subwavelength structured materials, commonly known as metamaterials owing to their extraordinary optical properties that hardly be found in natural materials [1,2]. These materials are used for a wide variety of novel applications, such as cloaks of invisibility [3–5], perfect lenses [6–9], perfect absorbers [10,11], sensor detections [12,13], super scatterer [14] and slow light devices [15]. By designing meta-atoms, electric and magnetic resonances of the incident electromagnetic radiations can be tailored beyond natural limitations.

By adjusting the arbitrarily values of the permittivity and permeability, metamaterials can be classified into different types such as double negative materials [16] (with simultaneously negative permittivity ε and permeability μ), single negative materials [17] (with individually negative permittivity ε or permeability μ), epsilon-near-zero metamaterials (with an ε near zero and a μ of unity), mu-near-zero metamaterials (with a μ near zero and an ε of unity), and matched impedance zero-index materials (in which both the permittivity and permeability are set to zero). Nowadays zero-index materials (ZIM), with both or individual permittivity and permeability near to zero [18,19], prevails among researchers in related fields due to their hyperphysical applications such as tailoring wave front [20,21], squeezing and tunnelling wave energy [22–25], waveguide bending [26], controlling energy flux [27], total transmission and refection in ZIM [28–32] and etc.

Enoch et al. presented that a ZIM can enhance the directive emission for an embedded source [33]; Ziolkowski demonstrated the possibility of designing a MIZIM [34]. Li et al. proved that there is a zero-n gap inside the zero volume refractive index material, which is different from the properties of Bragg gaps [35]. Silveirinha and Engheta studied an ENZ medium that can squeezed and tunnelled the electromagnetic (EM) waves in a narrow subwavelength waveguide to enhance the efficiency, that was later demonstrated experimentally in microwave frequencies [22,23]. Most recently, Hao et al. illustrated the possibility of total reflection or transmission occurring by introducing defects inside the ZIM in a waveguide [28]. Nguyen et al. showed that similar effects can be obtained when dielectric defects are introduced into the MIZIM, which offer an active control on transmission and reflection [29]. Xu et al. theoretically perused the possibility of inverting total reflection to total transmission in a ZIM waveguide by controlling the embedded defects [30]. The experimental fabrication of low-loss ZIM operated at optical wavelength of 1.55 μm was reported by Huang et al. Yangyang Fu et al. illustrated additional modes in a single defect waveguide [36].

Although great progress has been made on the field of ZIMs and MIZIMs, the interest of exploring new fantastic properties and applications is never seen down.

In this paper, we will represent the possibility of higher order modes excited with monopole mode when total transmission and total reflection occurring in a multi defect waveguide. This type of waveguides can be used in optical communications, waveguide bending, nonlinear optics and also by considering light focusing effect of these waveguide, they can also be used in bio sensing.

* Corresponding author.
E-mail address: m.zavvari@iaurmia.ac.ir (M. Zavvari).

http://dx.doi.org/10.1016/j.optcom.2017.07.034
Received 10 May 2017; Received in revised form 4 July 2017; Accepted 10 July 2017
0030-4018/

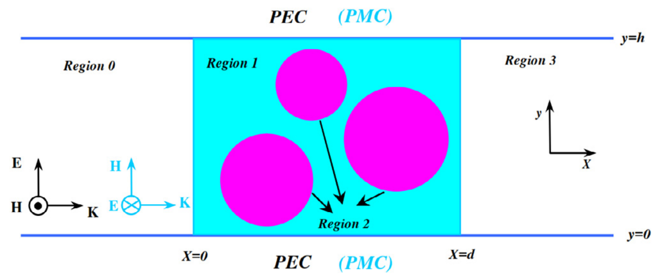

Fig. 1. Schematic of the proposed 2D waveguide with three defects. The (PMC) boundary is for TE polarized excitation.

The paper is organized as follows. In Section 2 we introduce the waveguide schematic and derive the formulas for each region. In Section 3 we apply the results to achieve higher modes excitations in the proposed configuration and finally in Section 4 the conclusions are drawn.

2. Waveguide structure

To begin with, consider a two-dimensional (2D) waveguide structure, as shown in Fig. 1, Region 0 and 3 are free space separated by a ZIM or MIZIM [region (1)] with the effective permittivity and permeability $\varepsilon 1$ and $\mu 1$, respectively. In general, electromagnetic parameters of region 1 are achieved by Drude medium theory:

$$\varepsilon_1 = 1 - \omega_{\mathrm{pe}}^2/[\omega(\omega + i\Gamma_{\mathrm{e}})] \qquad \mu_1 = 1 - \omega_{\mathrm{pm}}^2/[\omega(\omega + i\Gamma_{\mathrm{m}})] \tag{1}$$

where $\omega_{\mathrm{pe}} = \omega_{\mathrm{pm}} = \omega_{\mathrm{p}}$ indicate the plasma frequency and $\Gamma_{\mathrm{e}} = \Gamma_{\mathrm{m}} = \Gamma$ are related to the mean free path. Here we assumed that uniform and isotropic metamaterials are used, however anisotropic metamaterials are much easier to realize than isotropic materials. There are various methods to achieve these kind of materials such as metal–dielectric multilayered structures [37,38], metal wire arrays [39], etc. Region 2 consists of N cylindrical defects with relative electromagnetic parameters $\varepsilon_{2\mathrm{j}}$ and $\mu_{2\mathrm{j}}$ embedded in the host medium. We assume the incident beam of waveguide with a transverse magnetic (TM) polarization, $H_{in} = zH_{oz}e^{i(k0x-\omega t)}$ from the left port. For convenience, we omit the time variation term $e^{-i\omega t}$ from the incident wave equation. The walls of waveguide are set as PEC in order to minimize the propagation of TM wave with polarization along the y-axis of the waveguide. Outer boundaries can change into PMC in the case of transverse electric (TE) field radiation.

Based on Ampere–Maxwell equation, relationship between electric and magnetic field of each region can be written as:

$$\overrightarrow{E_j} = \frac{-1}{i\omega\varepsilon_0\varepsilon_j}\nabla \times \overrightarrow{H_j} \tag{2}$$

where the integer j indicates each region with the relative permittivity of ε_j. Then the magnetic and electric fields in region 0 should be written as:

$$\overrightarrow{H_0} = \hat{z}H_{0z}\left(e^{ik_0x} + Re^{-ik_0x}\right); \qquad \overrightarrow{E_0} = \hat{y}\frac{k_0}{\omega\varepsilon_0}H_{0z}\left(e^{ik_0x} - Re^{-ik_0x}\right). \tag{3}$$

Therefore, electromagnetic field in region 3 can be expressed as:

$$\overrightarrow{H_3} = \hat{z}TH_{0z}e^{ik_0(x-d)}; \qquad \overrightarrow{E_3} = \hat{y}\frac{k_0}{\omega\varepsilon_0}TH_{0z}e^{ik_0(x-d)} \tag{4}$$

where $\mathrm{k}_0 = 2\pi\mathrm{f/c}$ indicates the wave vector in free space and R and T represent the reflection and transmission coefficients, respectively. Because the region 1 is occupied by a medium with $\varepsilon_1 \approx 0$, then $\nabla \times \overrightarrow{H_1}$ must be zero in order to keep a finite E_1 so it is obvious that H_1has a constant value. By applying the boundary conditions at the interfaces of region 0 and 1, we have $H_{0z} + RH_{0z} = H_1$ and at interface of region 1 and 3, $T_{0z} = H_1$, which leads to $1 + R = T$.

We are now ready to calculate magnetic field inside each cylindrical defect by applying Helmholtz equation. Hence H_2 is propagating along the z-direction and we have:

$$\nabla^2\overrightarrow{H_z} + \mathcal{K}_2^2\overrightarrow{H_z} = 0 \tag{5}$$

where $\mathcal{K}_2 = \sqrt{\varepsilon_{2j}\mu_{2j}}k_0$, from Eq. (5) and cause

$$\frac{1}{r}\left[\frac{\partial}{\partial r}\left(r\frac{\partial\left(H_z\right)}{\partial r}\right)\right] + \frac{1}{r^2}\frac{\partial}{\partial\theta}\left(\frac{\partial H_z}{\partial\theta}\right) + \mathcal{K}_2^2H_z = 0. \tag{6}$$

If we insert $H_z = \Phi(r)\Theta(\theta)$ into the above equation we have:

$$\frac{d^2\Theta}{d\theta^2} + n^2\Theta = 0 \tag{7}$$

$$r^2\frac{d^2\Phi}{dr^2} + r\frac{d\Phi}{dr} + (\mathcal{K}_2^2r^2 - n^2)\Phi = 0 \tag{8}$$

where $\Theta(\theta) \cong e^{in\theta}$ and Eq. (8) affirms to generalized Bessel equation. Eq. (6) have two answers for inside and outside the cylindrical defects. So for the incident TM wave, the incident magnetic field in region 2, can be expressed as:

$$\overrightarrow{H_z^{in}} = \overrightarrow{H_2} = \hat{z}\sum_{j=1}^{N}\sum_{n=-\infty}^{\infty}a_{jn}J_n(k_{2j}r_j)e^{in\theta_j} \tag{9}$$

$$\overrightarrow{H_z^{out}} = \overrightarrow{H_{ZIM}} = \hat{z}H_1\sum_{n=-\infty}^{\infty}i^n[J_n(k_{1j}r) + \mathcal{B}_nH_n(k_{1j}r)]e^{in\theta_j} \tag{10}$$

where J_n is the nth order Bessel function of first kind and $k_{2j} = \frac{2\pi f}{c}\sqrt{\varepsilon_{2j}\mu_{2j}}$ is the wave vector in jth cylinder. H_{n} indicates the first type of nth order Henkel function and $\mathfrak{B}_n$ is the scattering coefficient.

Due to continuity of magnetic field at the interface of region (1) and (2), Dirichlet boundary conditions should be applied to Eq. (9), hence after some algebra we have:

$$\overrightarrow{H_2} = \hat{z}H_1\sum_{j=1}^{n}\left(\frac{J_0(k_{2j}r_j)}{J_0(k_{2j}R_j)} + \alpha_{jn}J_n(k_{2j}r_j)\cos(n\theta_j) + \beta_{jn}J_n(k_{2j}r_j)\sin(n\theta_j)\right) \tag{11}$$

where α_{jn} and β_{jn} are coefficients of the higher order modes and θ_j is relative angular coordinate in the jth cylinder. By combining Eqs. (2) and (11) the electric field inside each defect could be expressed as follows:

$$\overrightarrow{E_2} = iH_1\sum_{j=1}^{n}\left(\frac{J_1(k_{2j}r_j)}{J_0(k_{2j}R_j)} + \alpha_{jn}J_n'(k_{2j}r_j)\cos(n\theta_j) + \beta_{jn}J_n'(k_{2j}r_j)\sin(n\theta_j)\right)\sqrt{\frac{\mu_{2j}}{\varepsilon_{2j}}}\hat{\theta}_j. \tag{12}$$

We can now calculate transmission coefficient by applying Maxwell–Faraday theorem:

$$\oint\vec{E}\cdot\vec{dl} = -\iint\frac{\partial(\mu_0\mu_{2j}\overrightarrow{H_2})}{\partial t}\cdot ds. \tag{13}$$

The solution of Eq. (13) can be described as:

$$T = \frac{1}{1 - \frac{ik_0\mu_1(S-S_c)}{2h} - \frac{i\pi}{h}\sum_{j=1}^{N}\left[\frac{R_jJ_1(k_{2j}R_j)}{J_0(k_{2j}R_j)}\right]\sqrt{\frac{\mu_{2j}}{\varepsilon_{2j}}}}. \tag{14}$$

Here $S = d\times\mathrm{h}$ represents the entire area of ZIM and region 2, and S_{c} contributes to the total area of region 2. If no defects exists in the region 1 equation 14 decreases to:

$$T = \frac{1}{1 - \frac{ik_0\mu_1S}{2h}} = \frac{1}{1 - \frac{ik_0\mu_1d}{2}} \tag{15}$$

which implies that the transmission decays when length d increases and only when the total area of the channel is very small, the transmission coefficient will tend to unity. So in order to have a waveguide with normal dimensions, we used small sized random defects in the waveguide structure to confine the wave propagation.