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Investigation of characteristics of Terahertz double clad fiber made from negative index meta-material

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ABSTRACT

This study presents a double clad fiber with an inner and outer clad made from negative index materials. The mode matching method demonstrates the dispersion characteristics of the negative index material. The numerical results show that the parameters enable the meta-material double clad fiber work in the Terahertz band. The negative index material in double clad Terahertz fiber exhibits characteristics different from conventional fibers, such as a relatively wide TE mode transmission frequency band, stable frequency characteristics related to inner clad thickness, a broadband transmission effect in the HE mode under a low refraction index, and a relatively wider TE mode transmission band under a higher refraction index. This kind of negative index material in double clad Terahertz fiber may be implemented in Terahertz communication. Such an approach can be employed in a variety of frequency bands.

1. Introduction

In recent years, artificial electromagnetic materials have attracted more and more attention in the fields of physics, materials, and information science. This is due in part to these materials' characteristics that are not readily available in naturally occurring materials, such as negative refraction [1], the anomalous Doppler effect [1], and anomalous Cherenkov radiation [2]. Another advantageous and distinguishing property of artificial electromagnetic (EM) materials is that resonant structures can be designed over a large portion of the electromagnetic spectrum [3], ranging from microwave through Terahertz to near visible regimes.

Realization and performance analysis of various band meta-materials shows that they have great potential. One potential application involves utilizing artificial meta-materials to guide EM waves. Basharin [3] has analyzed the propagation of EM waves in planar waveguides manufactured from meta-materials and showed their antennas' unusual radiation properties. EM waves in sub-wavelength split-ring-resonator-loaded metallic waveguides have been simulated in [1]. One especially interesting application of meta-material devices is anisotropic meta-material waveguides [4,5]. Propagation of EM waves in meta-material waveguides [6–12] with negative permittivity and permeability is another application.

At present, the study of negative refractive index fibers is mainly focused on the transmission mode of single clad fibers. He et al. [13] studied the single-mode transmission area of the left-handed single clad fiber. Lu and Zi [14] analyzed the distribution of power and the relationship between refraction index and frequency. Negative refraction index materials are often filled with multi-clad fibers to optimize the transmission characteristics by adjusting the multiple parameters. Shen and Wang [15] proposed a kind of double clad fiber with a core made of negative index material and analyzed the dispersion properties of the TE_{01} mode. Hou et al. [16] presented a double clad fiber with its inner clad filled with negative index material. Use of the full vector method improves this fiber's transmission characteristics. However, there are few papers studying double clad fibers in which both the inner and outer clad are made of negative index material.

This study proposes a kind of double clad fiber with an inner and outer clad made of meta-material with a negative refraction index. The structure parameters make the double clad fiber work in the Terahertz band. Indeed, the specific fabrication suggests that the double clad fiber has properties that differ from conventional fibers'. We use the mode matching method to theoretically derive the dispersion equation, draw the dispersion curve, and explore the effect of the structure parameters and the negative index on the dispersion properties of the double clad fiber. In this fiber, the HE mode shows good single-mode transmission characteristics under a low refraction index and the TE mode shows good single-mode transmission characteristics under a higher refraction index. To some extent, this work will provide a theoretical basis for the potential

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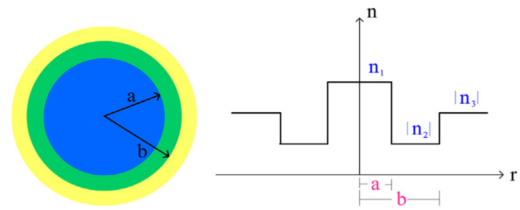

(a) Cross section view of the fiber (b) Refraction index distribution of the fiber

Fig. 1. Basic structure of the meta-material double clad fiber.

application of double clad negative index material fibers in THz communication systems.

2. Theoretical analysis

The basic structure of the proposed double clad fiber is shown in Fig. 1. Fig. 1(a) shows the cross section view of the meta-material double clad fiber, while Fig. 1(b) presents the refraction index distribution of the fiber core, inner clad, and outer clad. The fiber core ($r < a$) may be made with a positive refraction index dielectric, whereas the inner clad ($a < r < b$) and the outer clad ($r > b$) are made from negative refraction index meta-materials. The outer clad may extend to infinity in the radial direction. The medium parameters in these regions are characterized by μ_{ri}, ε_{ri} and n_i ($i = 1, 2, 3$), respectively, where μ_{ri} is the relative permeability of part i, ε_{ri} is the relative permittivity of region i, and n_i is the refraction index of region i.

In cylindrical coordinates, the longitudinal electric field and magnetic field satisfy the Helmholtz equation:

$$\nabla^2 H_Z + k_0^2 n^2 H_Z = 0, \tag{1}$$

$$\nabla^2 E_Z + k_0^2 n^2 E_Z = 0, \tag{2}$$

where H_z and E_z are the longitudinal magnetic field and electric field, respectively. Variable k_0 represents the wave number of the vacuum and n represents the refraction index of the dielectric. The solution of the Helmholtz equation is written as:

$$H_z = \begin{cases} A_1 J_m(Tr)\cos m\varphi e^{j\beta z} & 0 < r < a, \\ [B_1 I_m(\tau r) + C_1 K_m(\tau r)]\cos m\varphi e^{j\beta z} & a < r < b, \\ D_1 K_m(hr)\cos m\varphi e^{j\beta z} & r > b, \end{cases} \tag{3}$$

$$E_z = \begin{cases} A_1 J_m(Tr)\sin m\varphi e^{j\beta z} & 0 < r < a, \\ [B_2 I_m(\tau r) + C_2 K_m(\tau r)]\sin m\varphi e^{j\beta z} & a < r < b, \\ D_2 K_m(hr)\sin m\varphi e^{j\beta z} & r > b, \end{cases} \tag{4}$$

where $J_m(Tr)$, $I_m(\tau r)$, and $K_m(hr)$ are the m order Bessel function, the m order first-class modified Bessel function, and the m order second-class modified Bessel function, and T, τ, and h represent the transverse propagation constants of the fiber core, the inner clad, and the outer clad, respectively. As has been proved, they are related to the vacuum wave number k_0 and propagation constant β in the following manner:

$$T^2 = k_0^2 n_1^2 - \beta^2 = \omega^2 \mu_1 \varepsilon_1 - \beta^2, \quad \tau^2 = \beta^2 - k_0^2 n_2^2 = \beta^2 - \omega^2 \mu_2 \varepsilon_2,$$
$$h^2 = \beta^2 - k_0^2 n_3^2 = \beta^2 - \omega^2 \mu_3 \varepsilon_3. \tag{5}$$

Since the fiber core is composed of the dielectric with positive permittivity ε_1 and permeability μ_1, the refraction index n_1 in Eq. (4) should be positive and have the relation $n_1 = c\sqrt{\mu_1 \varepsilon_1}$ (c is the velocity of light). But for the inner and outer clad, the refraction index n_2 and n_3 should be negative and related to permittivity and permeability with $n_2 = -\sqrt{\mu_2 \varepsilon_2}$ and $n_3 = -\sqrt{\mu_3 \varepsilon_3}$, respectively.

As has been proved, the tangential electric and magnetic fields are continuous at the interface of the dielectric. Using the solution and the continuity of the tangential electric and magnetic field, the dispersion function is obtained as follows:

$$\begin{vmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{44} \end{vmatrix} = 0, \tag{6}$$

where $a_{11} = \beta m\left(\frac{1}{T^2 a} + \frac{1}{\tau^2 a}\right) I_m(\tau a)$, $a_{12} = \beta m\left(\frac{1}{T^2 a} + \frac{1}{\tau^2 a}\right) k_m(\tau a)$, $a_{13} = \frac{\omega\mu_1 I_m(\tau a) J'_m(Ta)}{T J_m(Ta)} - \frac{\omega|\mu_2| I'_m(\tau a)}{\tau}$, $a_{14} = \frac{\omega\mu_1 K_m(\tau a) J'_m(Ta)}{T J_m(Ta)} - \frac{\omega|\mu_2| K'_m(\tau a)}{\tau}$, $a_{21} = \beta m\left(\frac{1}{\tau^2 b} - \frac{1}{h^2 b}\right) I_m(\tau b)$, $a_{22} = \beta m\left(\frac{1}{\tau^2 b} - \frac{1}{h^2 b}\right) K_m(\tau b)$, $a_{23} = -\frac{\omega|\mu_2| I'_m(\tau b)}{\tau} + \frac{\omega|\mu_3| I_m(\tau b) K'_m(hb)}{h K_m(hb)}$, $a_{24} = -\frac{\omega|\mu_2| K'_m(\tau b)}{\tau} + \frac{\omega|\mu_3| K_m(\tau b) K'_m(hb)}{h K_m(hb)}$, $a_{31} = -\frac{\omega|\varepsilon_2| I'_m(\tau a)}{\tau} + \frac{\omega\varepsilon_1 I_m(\tau a) J'_m(Ta)}{T J_m(Ta)}$, $a_{32} = -\frac{\omega|\varepsilon_2| K'_m(\tau a)}{\tau} + \frac{\omega\varepsilon_1 K_m(\tau a) J'_m(Ta)}{T J_m(Ta)}$, $a_{33} = \beta m\left(\frac{1}{T^2 a} + \frac{1}{\tau^2 a}\right) I_m(\tau a)$, $a_{34} = \beta m\left(\frac{1}{T^2 a} + \frac{1}{\tau^2 a}\right) k_m(\tau a)$, $a_{41} = -\frac{\omega|\varepsilon_2| I'_m(\tau b)}{\tau} + \frac{\omega|\varepsilon_3| I_m(\tau b) K'_m(hb)}{h K_m(hb)}$, $a_{42} = -\frac{\omega|\varepsilon_2| K'_m(\tau b)}{\tau} + \frac{\omega|\varepsilon_3| K_m(\tau b) K'_m(hb)}{h K_m(hb)}$, $a_{43} = \beta m\left(\frac{1}{\tau^2 b} - \frac{1}{h^2 b}\right) I_m(\tau b)$, $a_{44} = \beta m\left(\frac{1}{\tau^2 b} - \frac{1}{h^2 b}\right) K_m(\tau b)$, where m is order of the mode, $|\mu_2|$ and $|\mu_3|$ are the absolute values of the inner clad and outer clad, and $J'_m(x)$, $I'_m(x)$ and $K'_m(x)$ are the first-order reciprocals of the Bessel function, the first-class modified Bessel function, and the second-class modified Bessel function, respectively. Thus, the dispersion curve of each mode can be plotted out easily according to the range of β.

However, we are more concerned with the TE mode and the TM mode. Let $m = 0$, identity (6) would be naturally simplified to the dispersion equation of the TE mode and the TM mode. For the TE mode, the dispersion equation should be:

$$\left(-\frac{\omega|\varepsilon_2| I'_m(\tau a)}{\tau} + \frac{\omega\varepsilon_1 I_m(\tau a) J'_m(Ta)}{T J_m(Ta)}\right) - \left(\frac{\omega|\varepsilon_2| K'_m(\tau b)}{\tau} + \frac{\omega|\varepsilon_3| K_m(\tau b) K'_m(hb)}{h K_m(hb)}\right)$$
$$- \left(-\frac{\omega|\varepsilon_2| I'_m(\tau b)}{\tau} + \frac{\omega|\varepsilon_3| I_m(\tau b) K'_m(hb)}{h K_m(hb)}\right)\left(-\frac{\omega|\varepsilon_2| K'_m(\tau a)}{\tau} + \frac{\omega\varepsilon_1 K_m(\tau a) J'_m(Ta)}{T J_m(Ta)}\right) = 0, \tag{7}$$

For the TM mode, the dispersion equation would be:

$$\left(\frac{\omega\mu_1 I_m(\tau a) J'_m(Ta)}{T J_m(Ta)} - \frac{\omega|\mu_2| I'_m(\tau a)}{\tau}\right)\left(-\frac{\omega|\mu_2| K'_m(\tau b)}{\tau} + \frac{\omega|\mu_3| K_m(\tau b) K'_m(hb)}{h K_m(hb)}\right)$$
$$- \left(-\frac{\omega|\mu_2| I'_m(\tau b)}{\tau} + \frac{\omega|\mu_3| I_m(\tau b) K'_m(hb)}{h K_m(hb)}\right)\left(\frac{\omega\mu_1 K_m(\tau a) J'_m(Ta)}{T J_m(Ta)} - \frac{\omega|\mu_2| K'_m(\tau a)}{\tau}\right) = 0, \tag{8}$$

3. Calculated results

Theoretical analysis shows that the dispersion property can be obtained though the dispersion equation. Identity (6) implies the relationship between β and ω. This allows the dispersion curves that indicate the relationship between β/ω and ω (or β/k_0 and k_0) to be drawn out. To make the EM wave focus on the core, we fill the high positive refraction index material's core with the parameters of $\mu_{r1} = 3$ and $\varepsilon_{r1} = 3$. But for the inner clad and outer clad, we chose a relatively low negative refraction index with parameters of $\mu_{r2} = -1$, $\varepsilon_{r2} = -1$, $\mu_{r3} = -1$, and $\varepsilon_{r3} = -4$. Thus, the range of β/k_0 should be $2 \leq \beta/k_0 \leq 3$. Fig. 2 shows the dispersion curves of the TE_{01} mode and the TE_{02} mode. The dispersion curves of the TE_{01} mode and the TE_{02} mode are plotted as the black lines. Fig. 1 shows that the cut-off frequency of the TE mode is relatively smaller, and the transmission band of the TE mode becomes wider in comparison to the fiber with a positive refraction index. In addition, the wave number of the vacuum ranges about from 21,510 to 44,656 for the