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Negative epsilon medium based optical fiber for transmission around UV and visible region

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ABSTRACT

Combination of negative epsilon metal (silver) with a dielectric (Al_2O_3/SiO_2) layer forms a metamaterial with anisotropic characteristics. This metal/dielectric composition supports the change in effective permittivity of the metamaterial based on the incident wavelength. Transmission of electromagnetic waves is made possible in this work, at very low wavelength around ultraviolet and visible region. Use of aluminum oxide and silver layers as metamaterial core in the fiber, efficient transmission in the subwavelength region is achieved. Frequency domain analysis is made, when another metamaterial with the combination of SiO_2 and silver layer is used, which shows the backward propagation of waves possible at the frequency of 847.45 THz.

Keywords: Metamaterial, Negative epsilon medium, Optical fiber, Subwavelength propagation.

1. INTRODUCTION

Optical fiber, being a key component of the fiber optic communication systems, has greater impact on transmitting the information in the form of light. The material used for designing the fiber determines the dispersion characteristics of the fiber, as the light is guided by the phenomenon of total internal reflection inside the fiber [1]. In general, fiber with lower dispersion and attenuation characteristics helps in efficient transmission of electromagnetic waves.So the choice of material for a fiber must be in such a way that it supports high transmission rate with lower dispersion characteristics. In this paper, metamaterials are used to design a fiber with low dispersion characteristics when the chosen metal/dielectric is equal in their concentration. Metamaterials are the artificial materials that can be engineered to have electromagnetic properties that are not usually found in nature [2], which have wider applications such as sub-diffraction imaging systems [3], surface plasmon waveguides [4] and most importantly on optical cloaking [5]. This unique properties and applications of metamaterial have attracted many researches in recent years.

In this paper, negative epsilon medium is structured with the help of silver, which naturally offers almost pure negative permittivity with small imaginary part at optical frequencies [6]. When silver is layered with a dielectric layer, it acts as ananisotropic metamaterial (AMM) [7]. Here, two different dielectrics are used in combination with silver nano-layer to structure two different metamaterial which exhibits unique properties based on the wavelength of incidence. Al_2O_3/Ag combination [8] aids the transmission of incident waves at subwavelength region when it is used as the core of the fiber and surface propagation of plasmons are brought out when the same anisotropic metamaterial is used in cladding of the fiber with hollow core.

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Use of SiO_2 layer with silver provides us with another metamaterial with anisotropic property [9] showing backward propagation of incident electromagnetic waves. Mode analysis is made to ensure the surface propagation at the cross-section of the designed fiber. Dispersion and confinement loss characteristics are analyzed for different incident wavelengths. Frequency domain analysis is also made, to realize the backward propagation in the fiber with Ag/SiO_2 as metamaterial.

2. DESIGN PHASE

2.1. Structuring of AMM fiber with Aluminum oxide as dielectric

An Electromagnetic wave travelling inside a medium considers two important parameters for propagation, which are permittivity and permeability. Here, the alternatively stacked layers of Al_2O_3/Ag are rolled up to form the cladding of the cylindrical waveguide with a hollow core. The value of permeability is considered to be unity (μ = 1) in this case and the effective permittivity tensor of the medium is calculated using the formula,

$$\left[{}^{eff}\right] = 0 - [1] \begin{bmatrix} \perp \cos^2(\varphi) + \sin^2(\varphi) & (\perp -)\sin(\varphi)\cos(\varphi)0 \\ (\perp -)\sin(\varphi)\cos(\varphi) & \perp \sin^2(\varphi) + \cos^2(\varphi) \\ 0 & 0 \end{bmatrix} \quad (1)$$

where [^{eff}] is the effective permittivity tensor and are the perpendicular and parallel components of the effective permittivity. This effective permittivity of the metamaterial with Al_2O_3 as dielectrichas both real and imaginary part that variesaccording to the wavelength. These perpendicular and parallel components of the effective permittivity is given by,

$$_{4\%}{}^{eff} = (C_m + C_d)_{\ m\ d} / (C_{m\ d} + C_{d\ m}) \quad [2]$$

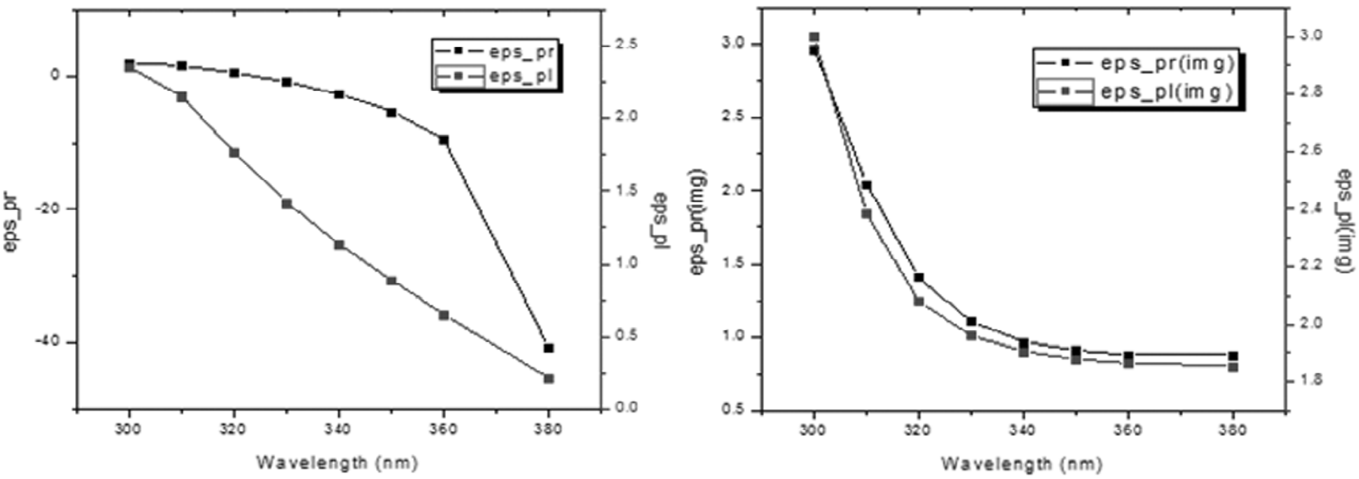
$$^{eff} = (C_{m\ m} + C_{d\ d})/ (C_m + C_d) \quad [3]$$

where $_m$ and $_d$ are the permittivity of the metal and dielectric respectively. C_m and C_d are the ratios of metal and dielectric respectively in the entire composition. Metals (like silver used here) have the ability to act as plasma at high frequency. The electrons are free to move around while the massive ions are more or less stationary. Solving this in plasma problem with incident electromagnetic waves, a resonance frequency called plasma frequency is obtained [10], which is related with the effective permittivity of the medium as,

$$[= [_0 \, [1-(\omega_p{}^2/\omega^2)] \quad [4]$$

where ω_p is the plasma frequency, above which the conduction of electrons cannot be excited properly to eliminate the incident electromagnetic waves. Now, these incident waves can pass through the metal as it propagates in a vacuum [11].

When the wavelength of incidence is changed, the corresponding values of the effective permittivities also changes, which leads to the change in propagation of the incident wave. This change in parallel and perpendicular permittivities of effective permittivity with respect to wavelength for metamaterial with Aluminum oxide as dielectric and Silver as metal is the evident of their anisotropy and is shown in the Fig 1(a) and 1(b) respectively. There occurs the possibility of surface plasmon propagation of the incident wave in the same fiber geometry designed with the same metamaterial used for normal core propagation, with the different wavelength of incidence. The entire design of fiber with AMM as clad and as core is shown in the Fig. 2. The stacking of layers with metal and dielectric followed by conversion in to cylindrical waveguide structure is shown in Fig. 2(a) and 2(b). The fiber loaded with AMM permittivity for cladding and core are shown in the Fig. 2(c) and 2(d) respectively.



(a) (b)

Figure 1: Variation of the calculated (a) Real part of perpendicular and parallel effective permittivity of AMM (Aluminum oxide as dielectric) with respect to wavelength. (b) Imaginary part of perpendicular and parallel effective permittivities of the same AMM with respect to the wavelength.

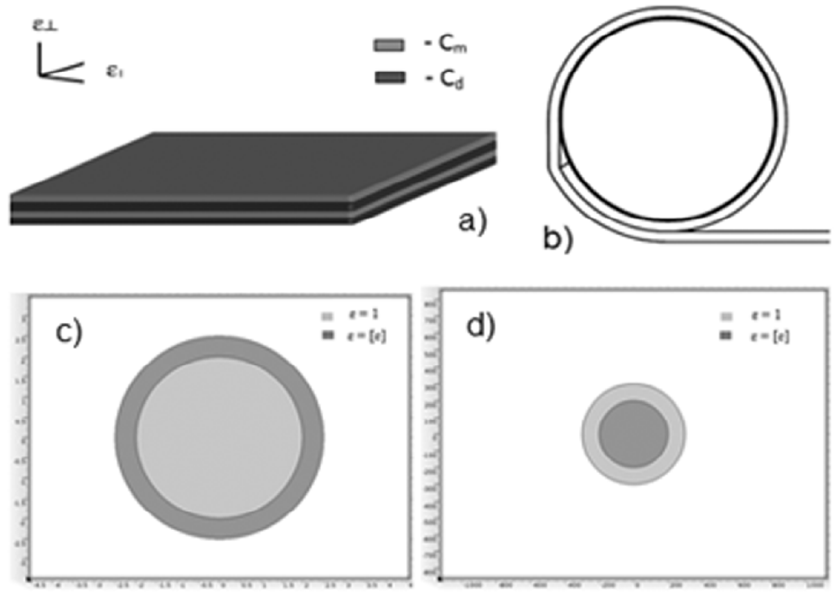


Figure 2: (a) Stacked nano-layers of metal (Ag of thickness 20 nm) and dielectric ($Al_2O_3$of same thickness) with C_m and C_d representing the concentration of metal and dielectric in the entire AMM composition. (b) Conversion of stacked layers to cylindrical waveguide with designed AMM as cladding and air in the core region. (c) Cross-section of the structured fiber with the core radius of 2µm and cladding layer of thickness 500 nm. The permittiviyt of air ([=1) and the effective permittivity [[] of metamaterial is loaded into the core and cladding respectively, which is shown in the insight. (d) Cross-section geometry of fiber with designed AMM as core, having the radius of 200 nm.

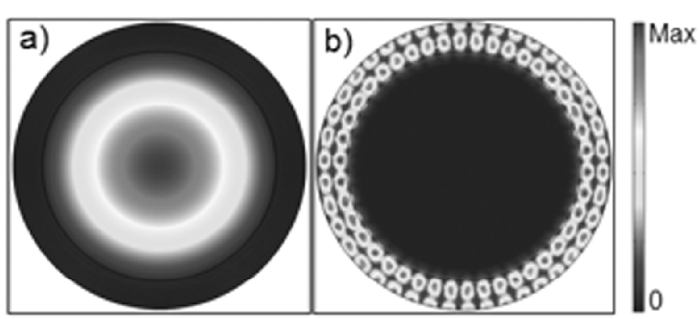


Figure 3: Mode analysis of the fiber with Al_2O_3 as dielectric in AMM (a) Normal core guidance at λ = 338 nm and (b) Surface propagationat λ = 323 nm in AMM clad fiber.

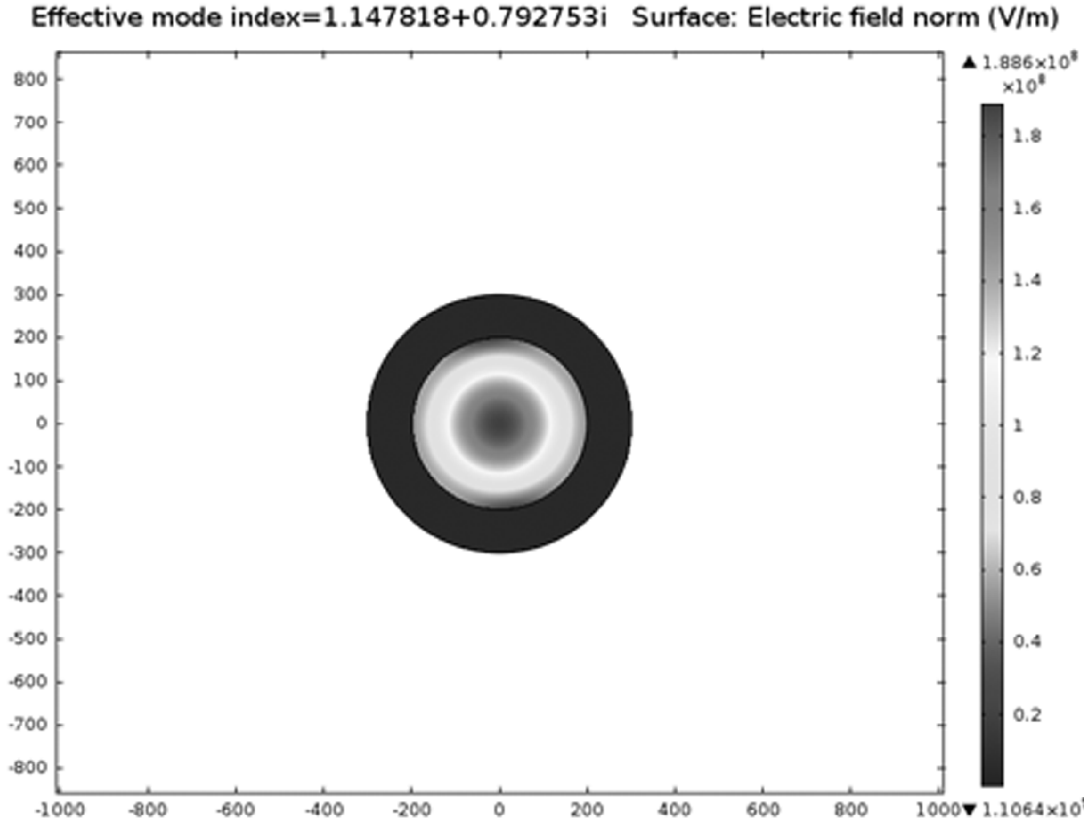


Figure 4: Mode analysis of the fiber with AMM core (Al_2O_3 as dielectric), supporting subwavelength surface plasmon propagation at the incident wavelength of 354 nm.

The mode analysis of the designed fiber with AMM cladding is shown in the Fig 3(a) and 3(b), which differentiates the normal core propagation and the surface plasmon propagation. Fig 4 shows the single mode propagation for AMM core fiber.

2.2. Hollow core fiber with Silicon dioxide as dielectric in AMM cladding

The concept of negative epsilon ([) is made easier with the use of metamaterials for optical fibers. Metamaterials with negative refractive index can be easily obtained if one of the two parameters ([and μ)is negative, as the refractive index considers the values of permittivity and permeability [12] as,

$$n = \sqrt{(\mu)} \qquad [5]$$

where and μ are the permittivity and permeability of the materials used. For simplification in calculation, we consider the value of permittivity to be negative and the value of permeability (μ) to be unity. Such materials are called Epsilon negative metamaterials. Therefore, the value of refractive index also turns out to be negative supporting backward propagation [13]. Fig 5.(a) and 5.(b) shows the ray diagram of normal and backward propagation of waves with positive and negative refractive index respectively. Combining Silicon dioxide with silver to form an AMM, serves well for such backward propagation of incident waves. As we need to observe the backward propagation in the designed AMM fiber with SiO_2 as a dielectric material, the design specifications are slightly modified compared to metamaterial with Al_2O_3 as dielectric. The effective permittivity of the metamaterial takes the tensor form, which is given as,

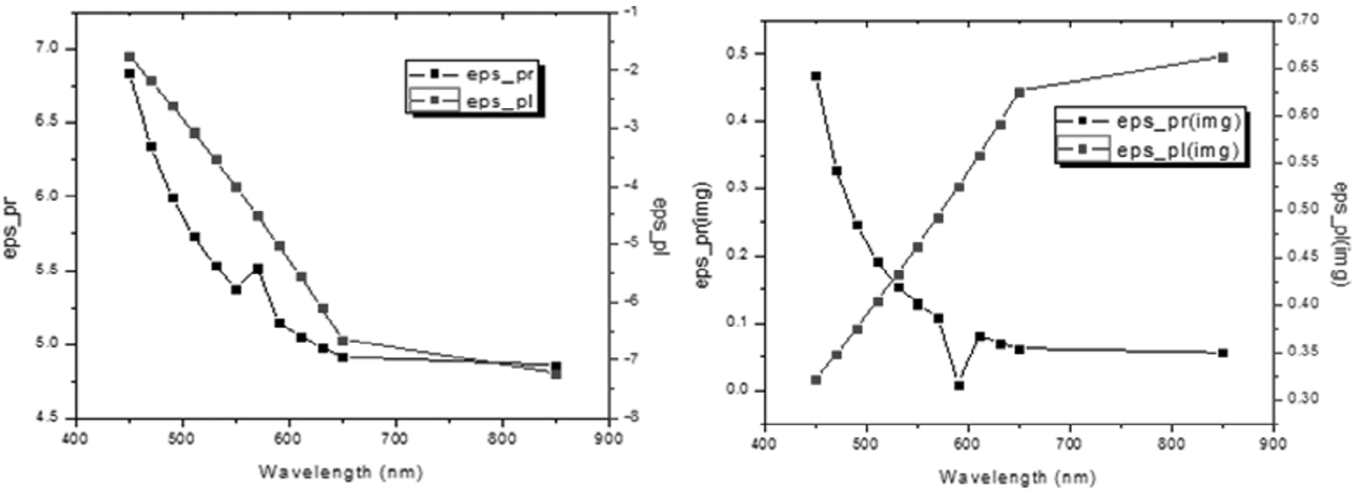
$$_{eff} = \text{diag}[\ _x,\ _y,\ _z,] \qquad [5]$$

The permittivities in the diagonal of the equation [5], $_x$, $_y$, and $_z$ is then described by the following equations [14] as,

$$_{x} = {}_{y} = (1 - N)\,{}_{1} + N\,{}_{2} \qquad [6]$$

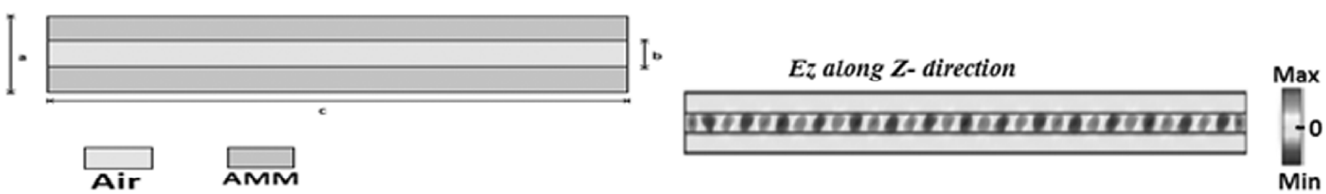
$$_{z} = {}_{12} / [N\,{}_{1} + (1 - N)\,{}_{2}] \qquad [7]$$

where $_1$ and $_2$ are the permittivity of SiO_2 and Silver layers that are combined to form AMM respectively and N is the volume fraction of the first medium. The anisotropy of the metamaterial with SiO_2 as dielectric and Silver (Ag) as metal is shown in the Fig. 5(a) and 5(b). The lateral section of designed fiber with Silicon dioxide as dielectric and silver as metal (with negative permittivity) as a metamaterial cladding and air in the core, is shown in the Fig. 6(a). The E-field propagation along the length of the structured fiber is shown in the Fig. 6(b). Analyses are made in the frequency domain in order to view the efficient backward propagation in the fiber as in Fig. 6(c).

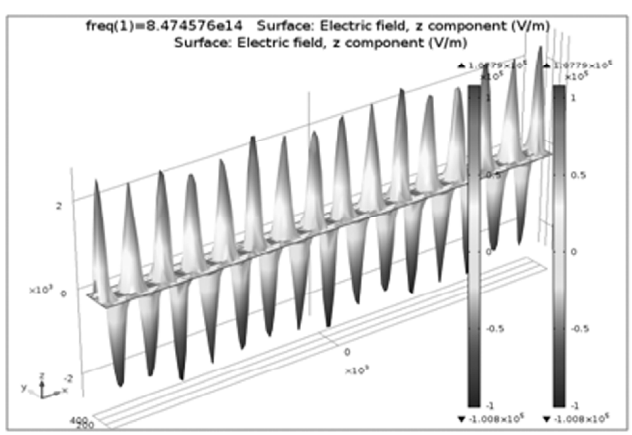


(a) **(b)**

Figure 5: Variation of the calculated (a) Real part of perpendicular and parallel effective permittivity of AMM (Silicondioxide as dielectric) with respect to wavelength.(b) Imaginary part of perpendicular and parallel effective permittivities of the same AMM with respect to the wavelength.



(a) **(b)**



(c)

Figure 6: (a) Lateral cross-section of the fiber with AMM cladding (Silicon dioxide as dielectric) having the geometric specifications as a = 600 nm, b = 200 nm, c = 10 µm. (b) Propagation of E-field along the z-direction of the geometry specified in Fig 6(a). (c) Three dimensional view of the wave propagation showing perfect backward propagation.

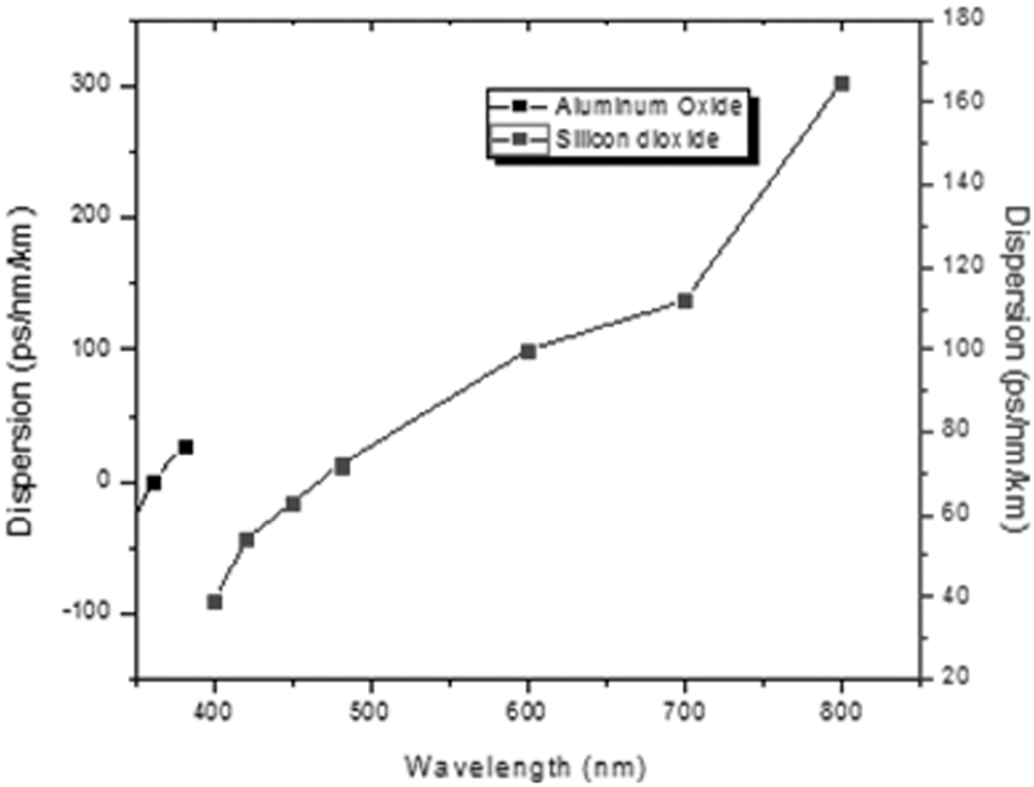


Figure 7: Dispersion characteristics of the fiber with AMM cladding for both Aluminum oxide and Silicon dioxide as dielectric. Black line represents the increasing dispersion curve for the metamaterial with Aluminum oxide as dielectric. Blue line represents the dispersion curve for the metamaterial with Silicon dioxide as dielectric, with silver as the metal in both cases.

The value of permittivities for silicon dioxide and silver are $_1$ = 3.9, $_2$ = -1.3416 respectively. The material parameters $_x$ and $_z$ are then calculated using the equations [6] and [7]. The determined effective permittivity tensor is loaded as the permittivity value of the metamaterial and frequency domain analysis is made for the given geometric specifications at the frequency of 847.45 THz.Dispersion characteristics of the fiber with AMM cladding (for both Aluminum oxide and Silicon dioxide as dielectric) are shown in Fig. 7. Black line shows the dispersion for metamaterial with Al_2O_3 as dielectric and Ag as metal around the ultraviolet region and the blue line is the dispersion for SiO_2/Ag combination of metamaterial as cladding. It is to be noted from the plot that the dispersion of the fiber increases with the increase in incident wavelength.

3. SUMMARY

In this paper, negative epsilon medium is used to observe different propagation characteristics in an optical fiber. Two different metamaterials with different geometrical specifications are used to manipulate light in different aspects. Anisotropy of metamaterials designed with Al_2O_3/SiO_2 as dielectric and silver as negative permittivity metal supports unique transmission properties. With Aluminum oxide as dielectric, subwavelength surface plasmon propagation is achieved at the wavelength of 342 nm. Backward propagation of waves is observed using frequency domain analysis of the metamaterial clad fiber that is designed with SiO_2as dielectric material at the frequency in the range of THz (here at 847.45 THz). Dispersion characteristics are plotted for both AMMs with different dielectrics, showing the lower dispersion at the lower wavelength over the range of 380 nm for Al_2O_3 as dielectric and 400 nm for SiO_2 as dielectric material.This subwavelength transmission helps in miniature in size of the waveguide and the backward propagation of electromagnetic waves finds applications in microwave imaging systems.

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