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Design of Low Loss Asymmetrical Photonic Crystal Fiber For Terahertz Communication

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Abstract- In this paper, we present the numerical simulation of photonic crystal fiber (PCF) design which exhibits zero flattened dispersion and birefringence at THz frequency in the range of 0.1 to 0.6 THz. Birefringence is introduced by breaking symmetry in cladding whole structure. Porous core and circular air-holes of different diameters have been used as cladding. This investigation reveals that significant birefringence of the order of $7.03138\text{x}10^{-11}$ and flat near zero dispersion of $1.85\text{x}10^{-33}$ ps/THz/m is achieved over frequency range of 0.1- 0.6 THz respectively. These types of PCF based THz waveguides are essential for beyond 5G and 6G communication.

Keywords: Photonic Crystal Fiber, Asymmetrical waveguide, Dispersion-flattened THz fiber, Cross sectional view of the proposed PCF, different frequencies in THz regime

I. INTRODUCTION

In digital world, technology plays a vital role in many aspects of human life. Over the last three decades the demands for data rates have doubled [1]. At this pace, the wireless communication systems will soon reach its entire capacity limit. Microwave spectrum gives narrow scope for data transmission [2] due to low frequency and bandwidth. Infrared spectrum has been exhausted much because of its fast transmission capability. Researcher's focus now shifted to the unused spectrum which lies in between infrared and microwave named TERAHERTZ band (frequency 0.1 - 10 THz (or) wavelength 3mm -30 µm). Due to lack of sources, detectors and suitable waveguides, most THz communication system is based on free space propagation [3]. Conventional guided medium like structure is needed due to the absorption loss, integration difficulty with other devices, high sensitivity. Stainless solid wires [3], dielectric coated tubes [4], and Bragg fibers [5] are some of the available THz waveguides. In such structures, most of the fields reside outside core, which in turn leads to increase in propagation loss and undesirable interactions with external environment [6]. Several other waveguides like parallel plates [7], metal wires [8], microwave waveguides [9] are also available. However, they have high losses in confinement. Hence, flexible and no ohmic loss materials like dielectric are required. Moreover, due to high losses because of absorption in THz regime, the usage of dielectric is also limited.

Among all types of THz waveguide, Photonic Crystal Fiber (PCF) based waveguide, designed for THz transmission, is a new type of micro-structured fiber. These special fibers have light confinement capability in hollow core and light captivity features which are not feasible on conventional optical fiber. Special characteristics of such PCF's are little bend loss and effective mode areas, low loss of confinement, high birefringence and sensitivity [10]. Enhanced confinement capability [11], less losses, dispersion tenability, and flexibility in structure [12] enabled the use of PCF in optical regime. Three different types of PCFs are available in Terahertz range. One such fiber which utilizes photonic band gap properties for guiding waves is hollow core fiber based on photonic crystals [13]. In this fiber considerable portion of THz field propagates in air. Second type is solid core - based PCF which guides the THz waves based on total internal reflection (TIR) principles [14]. In these fibers, maximum wave energy is transmitted in the core. However, these are not suitable for THz application due to high material losses. Another and most recent type of THz PCF which is also based on Total Internal Reflection principles is called porous fiber. Here, array of air holes in sub wavelength dimension are introduced next to core region [15] for confining field energy and to minimize propagation losses. The PCF's porous structure can take the shape of circle, hexagon, decagon, tetragon, quasi, octagon etc. [16]. Some important performance metrics of PCF in THz applications are birefringence [17], confinement loss, total loss, dispersion, power fraction, effective material loss, bending loss, effective refractive index, nonlinearity, sensitivity, beat length, numerical aperture, effective mode area, scattering loss, porosity, air core power fraction, splice loss, V-parameters, etc. [18]. Losses in THz PCF mainly represent losses due to confinement (CL) and material (EML). From the above-mentioned parameters, birefringence of high value is very important for polarization dependent sensing, filtering, guiding and splitting applications in THz region. Propagating field's state of polarization is maintained in highly birefringent fibers. Birefringence can be introduced in THz PCF designs by breaking geometric symmetry within cladding and/or core areas. PCF with high birefringent values having circular air holes in cladding with partially slotted and fully slotted rectangular core has been described in Ref. [19]. Tianyu Yang et.al [19], used two different materials like High resistivity silicon (HRS) & TOPAS to test the performance of their proposed design. After fabrication and testing, prototype attained a birefringence of 0.42-0.51 (HRS) at 0.7 THz and 0.82-0.88 (TOPAS) at 1.3THz with negligible dispersion in both the cases. The values of birefringence obtained in the above-mentioned paper out perform values obtained in existing PCF designs. Another important parameter of interest in design of PCF for Guided THz communication is to control dispersion.

II. DESIGN METHODOLOGY

Cross section of our proposed fiber configuration is shown in Figure 1. Our proposed design has cladding consists of four air hole rings in a circular fashion and a porous core in centre. Distance between two adjacent air-hole is called as pitch (Λ) in triangular lattice distribution. Background material is chosen as silica which has a fixed value of n = 1.45. d_1 and d are the diameters of the first and second, third, fourth cladding rings respectively. The relation between the diameter can be expressed as d = 4× d_1, where d_1 represents the diameter of 1st cladding ring. To obtain birefringence and near zero flat dispersion dimension of PCF are set to Λ= 25 μm, d/ Λ= 0.95, d_1=d/4. Here in our fiber design, a large circular cladding with diameter =5*d is employed to confine background material. Parameter sweep can be done to analyze the effects of varying diameter of the cladding and pitch on properties of the PCF.

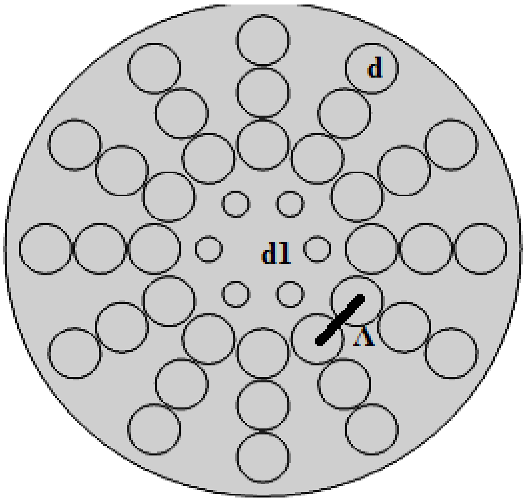

Figure 1. Cross sectional view of the proposed PCF.

III. PROPOSED DESIGN

In this paper, we proposed the design of PCF which has significant birefringence features and near zero flattened dispersion simultaneously. The proposed silicon-based PCF performance is compared for different range of THz frequencies. This PCF has cladding made of four air-hole rings and central porous core. In cladding diameter of circles are distinct for 1st layer and remaining 3 layers. It is well understood that closer the holes in cladding region, the more will be light confinement, which in turn gives low propagation loss. Porous core combined with geometrical asymmetry will leads to birefringence enhancement. Geometrical asymmetry is introduced by using first ring of cladding diameter as smaller than other cladding air holes. The parameters considered for testing performance of proposed PCF are as follows: Birefringence, Dispersion and Effective refractive index, Figure 1.shows the Cross sectional view of the proposed PCF.

Generally, two fundamental orthogonal polarization modes (HE_{11}^{x}, HE_{11}^{y}) were found in propagating fields. From such modes, birefringence (B) can be calculated as,

$$B(\lambda) = \|\, n_{eff}^{slow(x)} - n_{eff}^{fast(y)} \,\| \tag{1}$$

n_{eff}^{x}, n_{eff}^{y} = effective indices of fundamental mode of x & y polarization. In wideband transmission, inter-symbol interference is induced between neighboring pulses because of dispersion enabled broadening.

Hence, uniform and negligible dispersion over a wide range of frequency is desired in fiber designing which in turn can be calculated as,

$$\beta_2 = \frac{2}{c}\frac{dn_{eff}}{dw} + \frac{w}{c}\frac{d^2 n_{eff}}{dw^2} \tag{2}$$

n_{eff} = effective refractive index, $\omega = 2\pi f$ represents angular frequency of source. Effective refractive index plays an important role in propagation length of signal. Electric field (or) intensity drops to 1/e (or) $1/e^2$ from its initial value. It is called as propagation length.

$$\frac{I_0}{e^2} = I_0 e^{-2\alpha Z_p} \tag{3}$$

$$z_p = \frac{1}{\alpha} \tag{4}$$

$$\alpha = \frac{2\pi}{\lambda_0} k \tag{5}$$

Where k = imaginary part of complex effective refractive index.

IV. NUMERICAL RESULTS AND DISCUSSION

The proposed PCF is simulated using commercially available COMSOL Multi physics 5.3a version software which is based on finite element method. From the modal analysis as shown in Figure.2, Figure.3 it is clear that light confined in core region only. Performance indices of fibers like dispersion and birefringence values are given for various THz frequencies in Figure.4, Figure.5. From Table.1 it's clear that designed fiber has maximum propagation length at higher at f=0.6THz.

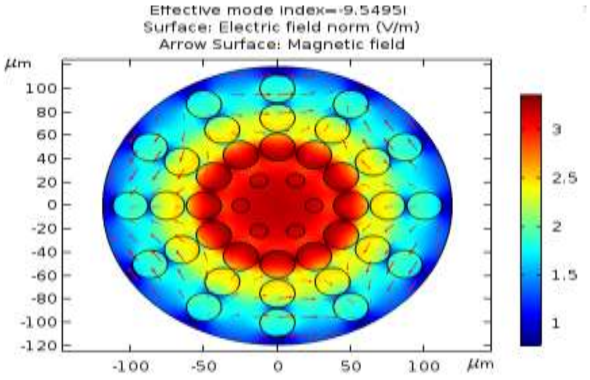

Figure 2. Modal analysis of proposed PCF (f=0.1THz)

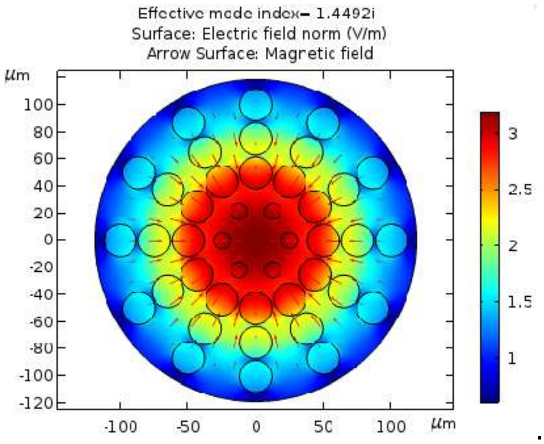

Figure 3. Modal analysis of proposed PCF (f=0.5THz)

Table 1. Effective Mode Index Of Proposed Fiber At Different Frequencies

Wavelength (mm)	**Frequency (THz)**	**Effective mode index**
3	0.1	9.5495i
1.5	0.2	4.6466i
0.9	0.3	2.9498i
0.7	0.4	2.0468i
0.6	0.5	1.4922i
0.5	0.6	0.98228i

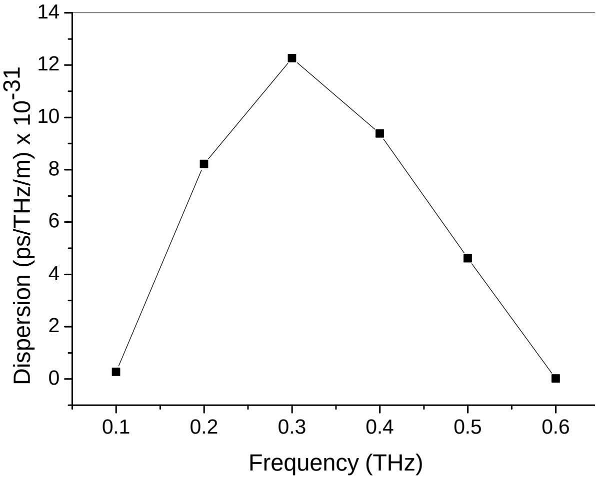

Figure 4. Dispersion of proposed fiber at different frequencies in THz regime

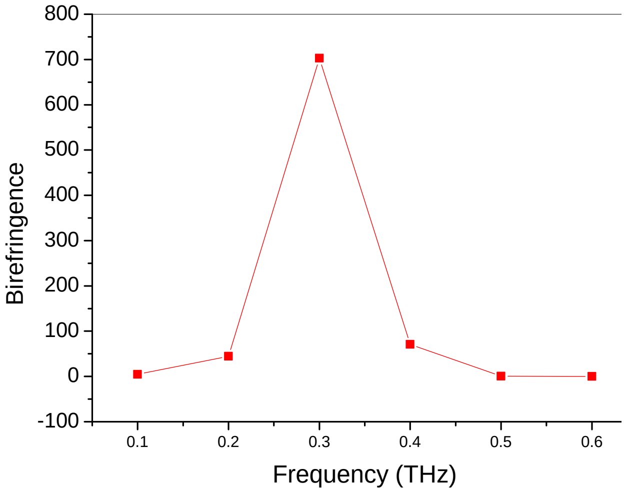

Figure 5. Birefringence values of proposed fiber at different THz frequencies

V. CONCLUSION

In this paper, we designed a circular PCF which has significant birefringence, near zero-flat dispersion over 0.1 - 0.6 THz frequency range. Our designed PCF shows flat zero dispersion of $1.85\text{x}10^{-33}$ ps/THz/m for 0.6 THz whereas the birefringence is maximum at 0.3THz. We used structural asymmetry whereas material asymmetry can also be introduced in cladding to further enhance parameters such as high birefringence and low dispersion at same frequency. By applying parameter sweep the guiding properties of fiber can be tested for various values of diameter and pitch. Our design holds easy fabrication capability because of circular shaped air-hole cladding and only porous core region. The work can be extended further for different THz material like TOPAS, COC etc., to test the performance of PCF. So, it will be a solution for further innovation of fiber devices in the THz regime.

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