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Highly birefringent and low effective material loss microstructure fiber for THz wave guidance

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ABSTRACT

A novel porous core photonic crystal fiber (PC-PCF) is proposed in this article for efficient transmission of terahertz (THz) wave. The propagation characteristics of the proposed design are investigated by finite element method based COMSOL v 4.2 software. The proposed PC-PCF offers ultrahigh birefringence of order of 10^{-2} and low effective material loss (EML) of 0.07 cm^{-1} at an operating frequency of 1 THz. Moreover, the proposed structure exhibits very low and nearly zero flattened dispersion of 1.1 ± 0.02 ps/THz/cm in the frequency ranging between 0.8 and 1.2 THz. In addition, very low bending loss of 5.45×10^{-9} dB/m is observed when bending radius is 1 cm. Other important guiding characteristics such as confinement loss, effective area *etc.* of the proposed fiber is discussed rigorously. This structure can be a promising candidate for different applications in THz regime.

1. Introduction

The electromagnetic waves having frequency range from 0.1 to 10 THz is defined as terahertz (THz) radiation band. Recently the spotlight of the researchers turned toward the narrowband frequency range because this frequency band has the immense potential to be used in sensing, imaging, biotechnology, security, spectroscopy and astronomy applications [1–4]. Moreover, THz pulse signal has important applications in non-invasive early diagnosis of skin cancer, including the basal cell carcinoma [5], dysplastic skin nevi and melanomas of hardly-accessible skin areas [6], minimally-invasive diagnosis of colon tissue cancers [7], and intraoperative diagnosis of breast tumors [8]. These promising applications of THz technology inspired the optoelectronics researchers to make concentrated effort in the development of better THz communication. As a result the THz source and detectors are available in the market [9,10]. On the other hand the THz waveguide is under research as the available THz waveguides are not enough efficient for THz wave propagation.

At the early stage dry air is used for the propagation of THz wave because it exhibits lowest dispersion and absorption than any other material. Nevertheless a number of problems arise such as uncertain absorption loss influenced by surrounding atmospheric conditions, transmitter receiver alignment related issues *etc.* due to the unguided medium. To solve this problem guided structure is proposed by the researchers. They show that THz wave can travel through all kind of conventional metallic waveguides [11]. The disadvantages of using metallic waveguide are high bending loss, low coupling efficiency and unstable guidance in complex surroundings. In order to solve this problem different guiding structures were offered by the researchers such as metal-coated dielectric tubes [12], Bragg band-gap fibers [13], plastic photonic band-gap fibers [14], sub-wavelength porous fibers [15], and hollow core fibers [16]. Unfortunately all the structures showed high absorption loss in THz radiation band. Finally, plastic sub-wavelength fibers and photonic crystal fibers (PCF) became the focal point due to the lower material loss, but solid core of the conventional PCF shows a high material absorption loss [17]. The easiest solution to solve high absorption loss is to introduce air holes in the core region. Introduction of air holes reduces the effective material in the core region and the EML reduces ultimately. This type of PCF is called porous core PCF (PC-PCF). Recently the spotlight has turned to this PC-PCF, which offers relatively lower absorption loss than solid core PCF [18,19]. Along with the low bulk absorption loss, birefringence is another important property for polarization maintaining waveguide. Birefringence is the absolute difference between the two refractive index of both x and y polarization mode. It can be made by breaking the symmetry of the core. Highly birefringent fiber can be applicable in different promising applications such as sensing, communication, polarized THz filtering

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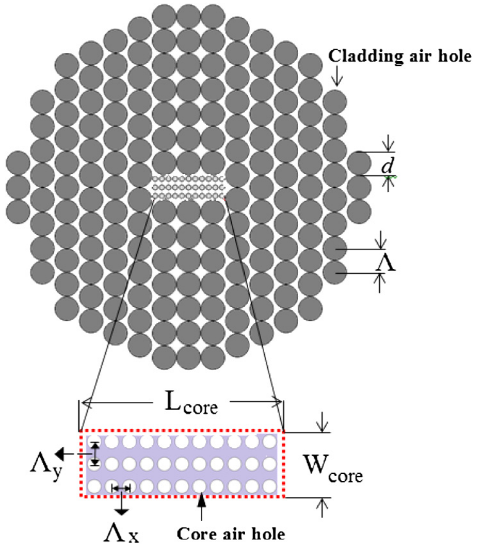

Fig. 1. Cross-sectional view of the proposed Microstructure Fiber.

etc. Numerous structures of PC-PCF were proposed by the researchers in recent past. A PCF with square lattice sub-wavelength air holes has been proposed in Ref. [20] that exhibits a very low birefringence of $1.26{\times}10^{-3}$. Asymmetrical sub-wavelength air-hole PCF [21] has been proposed by Atakaramians et al. that show a low birefringence of 1.2×10^{-2} at 0.65 THz. Besides Cho et al. demonstrated a triangular lattice plastic PCF [22] that exhibits birefringence as high as 2.1×10^{-2}. However, the EML was not reported in that article. A diamond core hexagonal lattice PCF is proposed in Ref. [23] which offered a birefringence of 0.017 and low EML of 0.07 cm^{-1} and 0.1 cm^{-1} at 0.7 THz and 1 THz respectively. Though the structure is simple, the birefringence is decreasing and the EML is increasing with the increase of frequency. That is why this PC-PCF might not be a good choice for higher frequencies.

However, in this paper we report a novel quasi hexagonal lattice PCF where the core is rectangular in shape. Due to the asymmetric type core, an ultra-high birefringence of 0.018 is achieved at 1 THz operating frequency. Moreover, a low EML of 0.07 cm^{-1} is shown by the PC-PCF at 1 THz. Dispersion flattened fiber is necessary for long distance communication and our proposed fiber offered nearly zero flattened dispersion of 1.1 ± 0.02 ps/THz/cm in the frequency ranging between 0.8 and 1.2 THz. Other important modal properties such as effective material loss, bending loss, effective area, and confinement loss are thoroughly discussed with the variation of different structural parameters.

2. Design methodology

The cross-sectional view of the proposed PC-PCF fiber is shown in Fig. 1. In the proposed design circular air holes are arranged vertically in the core region. The distance between two adjacent air-holes of the same column is called pitch (Λ). The distance between two adjacent vertical axes is also Λ and it is kept constant throughout the whole simulation. The cladding air filling fraction (d/Λ) was kept fixed at 0.95 throughout the analysis, where d is the diameter of the cladding air holes. Such high air filling fraction (AFF) has made the design compact. Due to the compactness the light is well confined in the core region and the EML and confinement loss reduces. For this particular PC-PCF, rectangular type core is chosen because the rectangular shape breaks the symmetry of the core which results high birefringence. Moreover, larger number of air holes can be introduced in the core for that structure than the circular and hexagonal structures. For any value of Λ the core length can be determined by $L_{\text{core}} = 3 \times \Lambda$ and the core width, $W_{\text{core}} = \Lambda$. In the core region total 33 circular air holes are arranged in 3 rows and each row contains 11 air holes. The distance between two adjacent air holes of same row is denoted as Λ_x and $\Lambda_x = 0.275 \times \Lambda$ and $\Lambda_y = 0.35{\times}\Lambda$ is denoted as the distance between two air holes of two adjacent row. Selection of this particular values offer maximum number of air holes without overlapping with each other. The background material considered for this design is cyclic olefin copolymer (COC), with a trade name of TOPAS having a refractive index of 1.5258, which is constant over 0.1–2 THz [24]. During the simulation, the bulk material absorption loss (α_{mat}) of 0.20 cm^{-1} has been inserted. Dry air is the most transparent medium for terahertz waves, having almost zero absorption loss ($\alpha_{\text{air}} = 0$). Therefore, at the time of calculation of various losses, α_{air} was not considered. This particular polymer is preferred due to some of its excellent merits over other polymers such as PMMA or Teflon. A circular perfectly matched layer (PML) boundary conditions outside the outer cladding is used in order to absorb the electromagnetic field propagating toward the surface. The PML thickness is about 10% of the total fiber diameter.

3. Numerical results and analysis

The finite element method (FEM) based software COMSOL *v*4.2 has been used to design and simulate the proposed PC-PCF. During the entire simulation, total 46,474 triangular elements, 5590 edge elements, and 796 vertex elements are required to represent the complete structure. The minimum element size has been taken as small as possible and which was about 0.3887 μm. The average element quality of the design was 0.9286. For efficient transmission of the THz wave, the electromagnetic field should be tightly confined in the core region. The mode field profile is shown in Fig. 2 and it is seen from the following figure is that the light is confined in the core region.

In a polarization maintaining PCF the birefringence is one of the vital property. It is dependent on the structure of the core. The birefringence of any PC-PCF can be calculated by using the following expression [23]

$$B = \left| n_x - n_y \right| \tag{1}$$

where B stands for birefringence, n_x and n_y indicates x and y polarization modes of the effective refractive index respectively. If the core is asymmetric then the birefringence is high. In the proposed design the dimension of the rectangular core is 3 × 1, so a high birefringence can be found from the proposed fiber. Fig. 3 shows the variation of birefringence of the proposed PC-PCF with the variation of core length for different core porosities. From the figure we can see that the birefringence increases with the increase of core length. This occurs because the change in core length is three times than the core width. As the core becomes more asymmetric with the increase of core length so the birefringence increases gradually. Again for a particular core length the birefringence increases with the increase of core porosity. This is because with the increase of core porosity the effective refractive index difference between the two polarization modes increases. From the graphical representation we can see that the maximum birefringence appears for 350 μm core length at 1 THz operating frequency for 20% core porosity. So, the optimal core length of the proposed fiber can be considered as 350 μm and the further numerical results will be highlighted for this particular core length. The maximum birefringence at optimum core length is 0.031, 0.24 and 0.18 at 20%, 30% and 40% core porosities respectively at 1 THz and it is better than the previous reported works [20–23]. Moreover, the birefringence of the proposed fiber at different frequencies for 20% core porosity at optimal core length is shown in Fig. 4. From the following figure we can see that the birefringence is high and this fiber can be used for different THz applications where high birefringence is necessary from 0.5–1.1 THz frequency band.

Now we analyze the most important guiding property of THz waveguide is effective material loss (EML) or effective absorption loss or bulk absorption loss. The EML indicates the total amount of light energy that