Current Optics and Photonics
Vol. 1, No. 6, December 2017, pp. 567-572

ISSN: 2508-7266(Print) / ISSN: 2508-7274(Online)
DOI: https://doi.org/10.3807/COPP.2017.1.6.567

Ultrahigh Birefringence and Extremely Low Loss Slotted-core Microstructure Fiber in Terahertz Regime

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(Received November 19, 2016 : revised August 14, 2017 : accepted November 10, 2017)

A novel slotted-core hexagonal photonic crystal fiber (PCF) for terahertz (THz) wave guiding is proposed in this paper. A trade-off managed between effective material loss (EML) and birefringence for efficient guidance of THz waves is illustrated in this article. The rectangular slot shaped air-holes break the symmetry of the porous-core which offers ultra-high birefringence of 8.8×10^{-2}. The proposed structure offers low bending loss of 1.07×10^{-34} cm^{-1} and extremely low effective material loss (EML) of 0.035 cm^{-1} at an operating frequency of 1.0 THz. In addition other guiding properties such as power fraction, dispersion and confinement loss are also discussed. The proposed THz waveguide can be effectively used for convenient transmission of THz waves.

Keywords : Fiber design and fabrication, Micro-structured fibers, Birefringence, Dispersion
OCIS codes : (060.2280) Fiber design and fabrication; (060.4005) Microstructured fibers; (260.1440) Birefringence; (260.2030) Dispersion

I. INTRODUCTION

Terahertz (THz) radiation indicates the band of waves whose frequency ranges from 0.1 to 10 THz. Recently, the spotlight of the researchers has turned towards this special narrow-band radiation due to numerous potential applications such as sensing, imaging, spectroscopy, communication, security and medical science [1-3]. With the advancement of the ongoing technology, the THz source and detector are already commercially available in the market [4]. However, the design of the optical waveguide is under experiment because almost all materials which are used for optical fiber waveguide construction absorb light when light propagates through them. At the early stage, an unguided medium (air) is used for the transmission of the THz wave. As a result, numerous problems arise such as transmitter-receiver alignment related issues, uncertain absorption loss influenced by surroundings atmospheric condition etc. To get rid of this problem, different guided media are proposed by the scientists such as metallic waveguides [5], metal-coated dielectric tubes [6], Bragg band-gap fibers [7], plastic photonic band-gap fibers [8], sub-wavelength porous fibers [9], hollow core fibers [10] for the efficient transmission of THz signal. However, all guided media showed high absorption of THz waves. Then photonic crystal fiber (PCF) came to light.

Moreover, the solid core of the PCFs result in high effective material loss (EML) [11]. Low-loss PCF has important application in the field of diagnosis of skin cancer, breast cancer, dysplastic skin nevi and hard-to-access skin areas [16]. Again low loss PCF is widely used in bio sensing applications. So, design of low loss PCF became a new challenge for the researchers. One possible solution to reduce the EML of PCF is to introduce air holes in the core region. Introduction of air holes in core reduces the effective material in the core region and the EML reduces ultimately. This type of PCF is called porous core PCF (PC-PCF).

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Color versions of one or more of the figures in this paper are available online.

Birefringence is another important property for both solid core PCF and PC-PCF. Birefringence is the absolute difference between the refractive indices of x and y polarization modes. We know that light is an electromagnetic wave is polarized when it propagates. The amount of polarization through the PCF depends on the structure of the medium. If the core is symmetrical along with the x-axis and y-axis, then the refractive indexes of the material are the same for both polarization modes and the birefringence is absent. Birefringence can be made by breaking the symmetry of the core intentionally. Highly birefringent PCF has important applications in sensing, imaging, medical science *etc*. [13]. Numerous designs of porous core PCF proposed by researchers show high birefringence. Islam *et al.* [12] proposed a porous core PCF which show an ultrahigh birefringence of 4.5×10^{-2} and EML of 0.08 cm^{-1} at an operating frequency of 1.0 THz. Hasanuzzaman *et al.* [13] proposed a slotted-core circular lattice PC-PCF which showed an ultrahigh birefringence of 7.5×10^{-2} and EML of 0.07 cm^{-1} at 1.0 THz. However, one major drawback of this design is that two different pitches (distance between two adjacent air holes, denoted by Λ) are used and it is very difficult to maintain different pitches at a same time during fabrication. Furthermore, Hasan *et al.* [14] has proposed a kagome lattice PC-PCF which showed high birefringence of 8.22×10^{-2} and EML of 0.05 cm^{-1} at 1.0 THz operating frequency. Though this structure showed high birefringence and low EML, the fabrication of kagome lattice is very difficult to fabricate. Bending loss is also an important parameter of a PC-PCF for the practical implementation of THz system. In some particular applications (such as terahertz sensing, biomedical imaging, *etc.*) it is important to maintain minimum EML with very low bending loss.

In this paper, we propose a slotted core hexagonal porous core PCF. The hexagonal shaped PCF is more compact than other types of structures and the light is well confined in the core region. The slotted core breaks the symmetry of core and an ultrahigh birefringence of 8.8×10^{-2} is shown by the proposed design. Due to the compactness of the fiber the light is well confined for high core porosities and the EML and bending loss is reduced. The lowest EML and bending loss are 0.035 cm^{-1} and 1.075×10^{-34} cm^{-1}, respectively, shown by the proposed fiber at 1.0 THz operating frequency respectively. The other guiding properties such as confinement loss, power fraction and, dispersion are discussed rigorously. The physical structure and fabrication feasibility are discussed in Section II. Section III covers the simulation results and the discussions. The conclusion are contained by Section IV.

II. DESIGN METHODOLOGY

The cross sectional view of the proposed PC-PCF is shown in Fig. 1. In the cladding region a hexagonal shaped structure with four rings is chosen. Two main reasons for choosing the hexagonal structure are that it provides better confinement of the light and eliminates the drawbacks of the design proposed in [14]. In a hexagonal shaped structure only one Λ is required for the designing purpose and high air filling fraction (AFF) provides compact design.

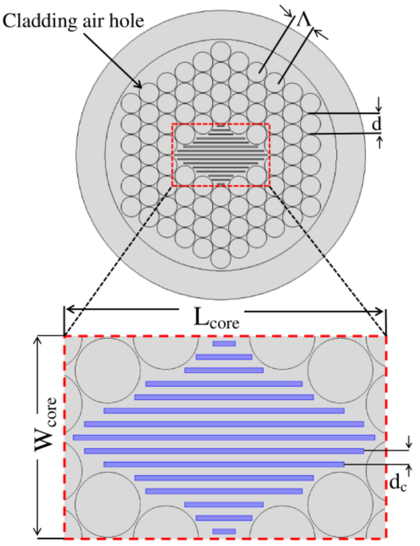


FIG. 1. The cross-sectional view of proposed porous core PCF.

The AFF is kept fixed at 0.96 throughout the whole numerical simulation. The main reason for choosing such a high value of AFF is that the EML decreases with the increase of the AFF. In the proposed porous core PCF, the principal design parameter is the length of the diamond shaped core (L_{core}) because the fiber dimension is determined by it. The width of the core (W_{core}) changes according to the L_{core}. The core length is determined as $L_{core} = 6\Lambda \cos 30° - d$, where d is the diameter of the cladding air hole. The core consists of 15 slots and the length of each slot is related to the core length (L_{core}). The length of the center slot is $4.5 \times L_{core}$. The slot lengths of the other slotted air holes are $4.15 \times L_{core}$, $3.5 \times L_{core}$, $2.66 \times L_{core}$, $2.33 \times L_{core}$, $1.16 \times L_{core}$, $0.83 \times L_{core}$ and $0.33 \times L_{core}$ respectively, arranged away from the center slot. These particular values are chosen because these values provide maximum birefringence. The slot-lengths are kept fixed throughout the analysis. For different porosities the slot-width (which is same for all slots) is varied. The core pitch (d_c) is defined as the horizontal center-to-center distance between two adjacent slots, which is selected as $0.2 \times \Lambda$. This particular value provides the entrance of a maximum number of slotted air holes without overlapping. The background material considered for this design is cyclic olefin copolymer (COC), with a trade name of TOPAS. It has a refractive index of 1.5258, which is constant over 0.1 - 2 THz [17]. During the simulation, the bulk material absorption loss (α_{mat}) of 0.20 cm^{-1} has been inserted. Dry air having almost zero absorption loss ($\alpha_{air} = 0$) is the most transparent medium for terahertz waves. Therefore, at the time of calculation of various losses, α_{air} was not taken into account. This particular polymer is preferred due to some of its excellent merits over other polymers such as PMMA or Teflon.

The proposed PCF consists of hexagonal lattice and slotted air holes in the core. The extrusion technique proposed by Kiang *et al.* [17] permits fabrication of almost any structure that might be used to extrude the slotted air holes. Therefore, it is anticipated that fabrication of the proposed structure is readily possible using the existing technologies.

III. SIMULATION RESULTS AND DISCUSSIONS

The finite element method (FEM) based software COMSOL v. 4.2 has been used to design and simulate the proposed PC-PCF. A circular perfectly matched layer (PML) boundary condition outside the outer cladding is used in order to absorb the electromagnetic field propagating towards the surface. During the entire simulation, total 29,271 triangular elements, 3516 edge elements, and 396 vertex elements are required to represent the complete structure. The minimum element size has been taken as small as possible at about 0.42 µm. The average element quality of the design was 0.9155. The PML thickness is about 10% of the total fiber diameter. 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.

At first, we demonstrate the birefringence property of the proposed fiber. Birefringence is the absolute difference between the refractive indices of x and y polarization modes expressed as [12]

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

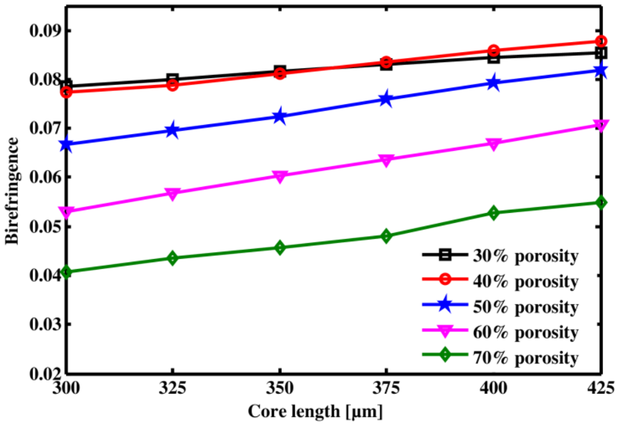
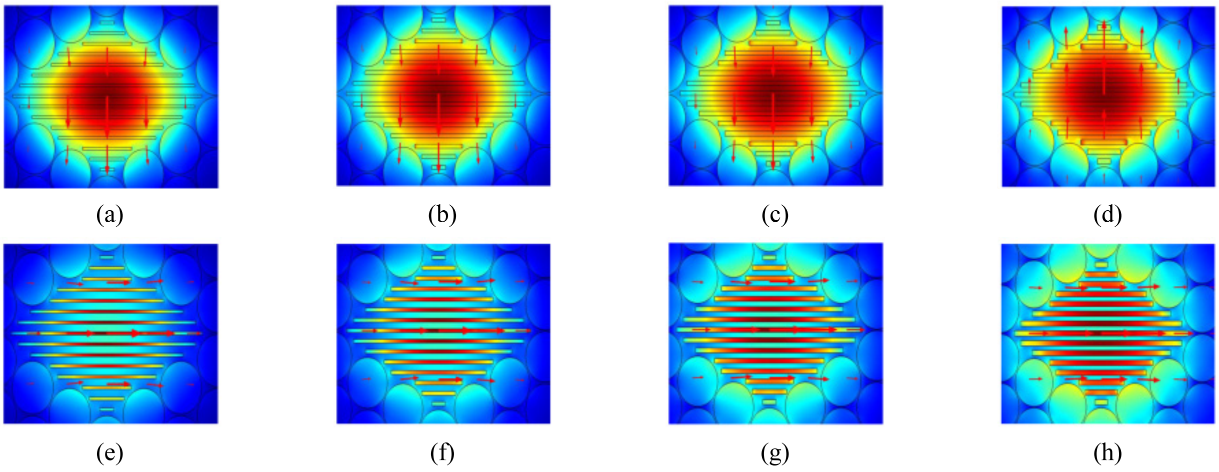


FIG. 3. Birefringence as a function of core length for different core porosities at 1 THz.

where *B* stands for birefringence, n_x and n_y indicate effective refractive indices of x and y polarization modes respectively. Figure 3 shows the birefringence as a function of L_{core} at different core porosities. From Fig. 3 it is seen that birefringence reduces when porosity increases. This happens because increase of porosity reduces the differential index contrast between the core and cladding. The maximum birefringence of the proposed fiber is 8.8×10^{-2} for 425 µm core length which is better than previous work in [12-14]. To the best of our knowledge, this is the maximum birefringence that has ever been reported in the THz regime 1.0 THz. Figure 4 shows the birefringence as a function of frequency. The birefringence increases with the increase of frequency as the transparency of air increases with the increase of frequency. The maximum birefringence is 0.096 at 1.5 THz when core length is 425 µm and porosity is 40%.


(a) (b) (c) (d)

(e) (f) (g) (h)

FIG. 2. Mode field distribution of the proposed fiber for (a) 30% porosity, x-pol (b) 40% porosity, x-pol (c) 50% porosity, x-pol (d) 60% porosity, x-pol (e) 30% porosity, y-pol (f) 40% porosity, y-pol (g) 50% porosity y-pol (h) 60% porosity, y-pol at 1.0 THz operating frequency.

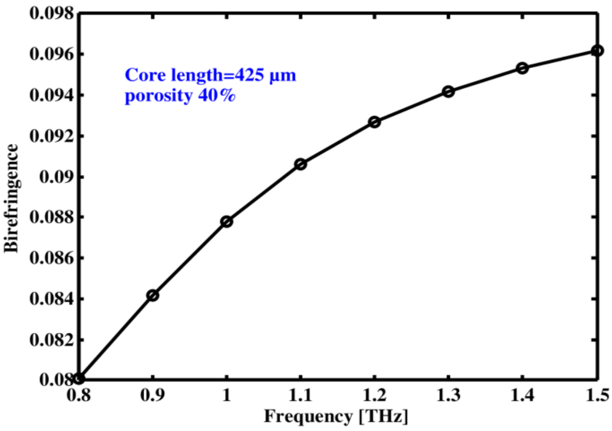


FIG. 4. Birefringence as a function of frequency for 40% core porosity and 425 μm core length.

The EML of a porous core PCF can be calculated as [13]

$$\alpha_{eff} = \frac{\left(\frac{\varepsilon_0}{\mu_0}\right)^{\frac{1}{2}} \int_{A_{mat}} n\,\alpha_{mat} |\mathrm{E}|^2 \, d\mathrm{A}}{2\int_{All} S_z \, d\mathrm{A}} \tag{2}$$

where ε_o and μ_o are the permittivity and permeability of vacuum, n_{mat} is the refractive index of the material used, E is the modal electric field, α_{eff} is the bulk material absorption loss and S_z is the z-component of the Poynting vector and $S_z = 1/2(\mathbf{E} \times \mathbf{H}).z$. The EML of the proposed slotted core fiber is shown in Fig. 5. We can see from Fig. 5 that the EML decreases with the increase of the core porosity. EML is the amount of light energy which is absorbed by the core material itself. The amount of core bulk material decreases with the increase of core porosities. That's why the EML reduces significantly for the PC-PCF over solid core PCF. The proposed fiber offers a low EML of 0.035 cm^{-1} which is better than previous reported work in [12-15].

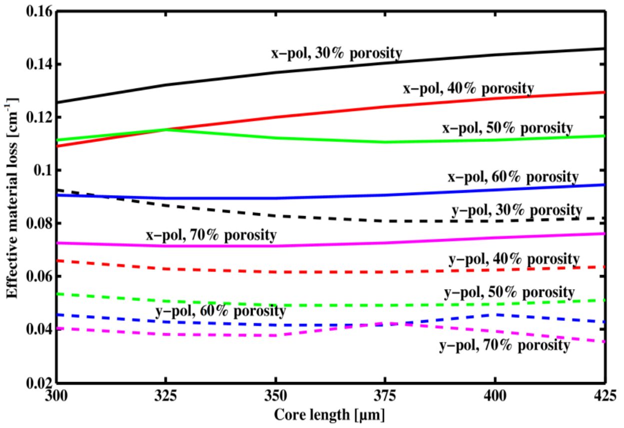


FIG. 5. EML as a function of core length for various porosities at 1 THz.

Bending loss is very important for the practical implementation of optical fiber waveguide. The bending loss can be quantified by using the following formula [15]

$$\alpha_{BL} = \frac{1}{8}\sqrt{\frac{2\pi}{3}}\frac{1}{A_{eff}}\frac{1}{\beta}F\left[\frac{2}{3}R\frac{\left(\beta^2-\beta_{cl}^2\right)^{3/2}}{\beta^2}\right] \tag{3}$$

where R is the bending radius, $F(x) = x^{-1/2}e^{-x}$, the propagation constant β and β_{cl} are defined as $\beta = 2\pi n_{co} / \lambda$ and $\beta_{cl} = 2\pi n_{cl} / \lambda$ for core and cladding, respectively, and A_{eff} is the effective area. The bending loss of the proposed fiber is shown in Fig. 6 and the following figure shows that the bending loss decreases with the increase of the frequency. The bending loss is not shown in [12-14]. The bending loss of the proposed fiber is 1.075×10^{-34} cm^{-1} at 1.0 THz operating frequency which is lower than the previous work [15]. To the best of our knowledge this is the lowest bending loss that has ever been reported.

Confinement loss is a phenomenon whereby part of the guided light penetrates in the cladding region. The confinement loss is not avoidable and it exists in every porous core PCF. The confinement loss of a PC-PCF can be calculated by using the following formula [12]

$$\alpha_{CL} = 8.686 \times \frac{2\pi f}{c}\mathrm{Im}(n_{eff}) \tag{4}$$

where f is the frequency of the guiding light, c is the speed of light in vacuum and $\mathrm{Im}(n_{eff})$ is the imaginary part of the effective index of the guided mode. The confinement loss of the proposed fiber is shown in Fig. 7. The confinement loss is $6.31 \times 10^{-3}\mathrm{cm}^{-1}$ at an operating frequency 1.0 THz and it is better than the previous work [12-13, 15].

Now, the mode power fraction of the proposed fiber is discussed. It is desired that maximum power travels through the air holes of the core. The fraction of power is calculated by the following expression [14]

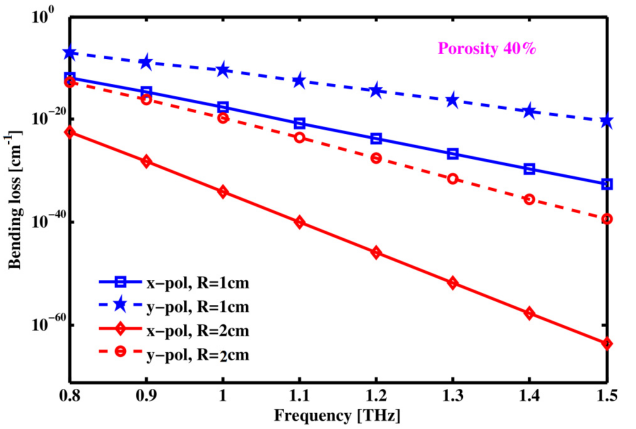


FIG. 6. Bending loss as a function of frequency at L_{core} = 425 μm.

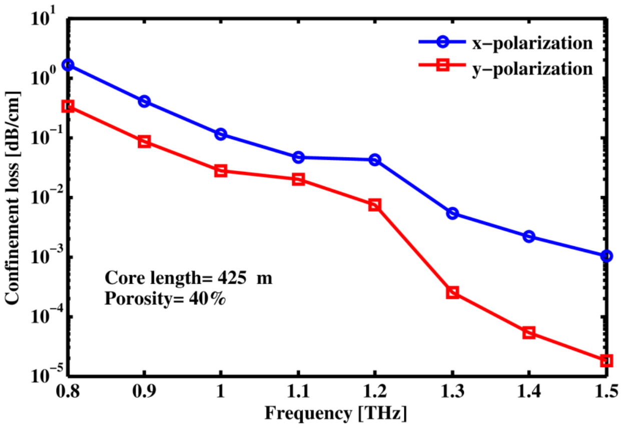


FIG. 7. Confinement loss as a function of frequency of the proposed fiber.

$$\eta = \frac{\int_X S_Z dA}{\int_{All} S_Z dA} \tag{5}$$

where X is the region of interest through which the power is to be calculated. The mode fraction power is reported in Fig. 8 and the figure represents that almost 42% of the total power travels through the core air holes and it is better than previous work in [13].

Lastly, the dispersion of the proposed fiber is discussed now. The high dispersion limits the data transmission rate and for efficient transmission the dispersion must be as low as possible. The dispersion is calculated by the following expression [13]

$$\beta_2 = \frac{1}{c}\left(2\frac{dn}{d\omega} + \omega\frac{d^2 n}{d\omega^2}\right) \tag{6}$$

where $\omega = 2\pi f$, f is the frequency of the light wave and c is the velocity of light in vacuum. Figure 9 shows the dispersion of the proposed slotted core PCF. From Fig. 9 it is seen that the variation of β_2 is less than 0.6 ps/THz/cm within the frequency range1-1.4 THz. This is comparable with the previous work in [13].

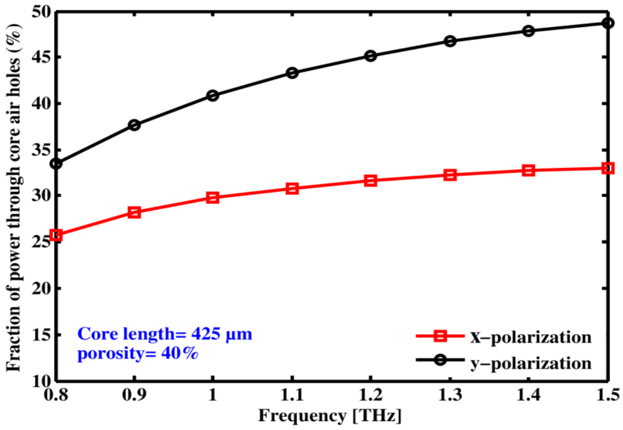


FIG. 8. Fraction of power through the core air holes as a function of frequency.

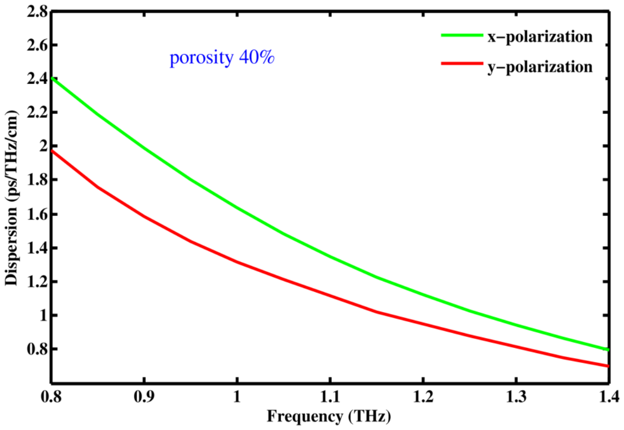


FIG. 9. Dispersion characteristics for x-polarization and y-polarization at L_{core} = 425 µm.

IV. CONCLUSION

An efficient slotted-core PCF has been analyzed for polarization maintaining applications. The proposed model presents extremely high birefringence of 0.088 and a very low effective material loss of 0.035 cm^{-1} at 1.0 THz operating frequency. The structure is expected to be fabricated using the ongoing fabrication technology combining extrusion techniques. The proposed structure is compact and robust and it would be an efficient guiding structure for THz wave transmission.

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