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A Novel Octagonal Shaped Porous Core Microstructure Bend Insensitive Fiber for Low Loss THz Wave Transmission

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Abstract:- A newfangled octagonal-shaped porous-core photonic crystal fiber (PCF) with hexagonal cladding is suggested for extraordinarily low loss THz wave propagation. The TOPAS based proposed fiber has achieved nearly inconsiderable bending loss of $6.5\times10^{-18}\mathrm{cm}^{-1}$, ultra-small confinement loss of 5.84×10^{-5} dB/cm and a flat material loss of 0.057 cm^{-1} at 1 THz operating frequency. Further study includes a high-power fraction of core which is about 42% with optimal design parameters. Finite element method (FEM) and circular perfectly matched layer (PML) boundary conditions were used for the characterization of the suggested PCF. The proposed fiber can be used for functional broadband THz communication and low loss application with fabrication feasibility.

Keywords:- *Finite Element Method, Bending Loss, Effective Material Loss, Terahertz Guidance, Confinement Loss, Photonic Crystal Fiber.*

I. INTRODUCTION

Many efforts are devoted recently for coming up with porous core photonic crystal fiber (PC-PCF) that has various and versatile applications within the atmospherical channel. Terahertz (THz) waveband that on paper lies in between 1-10 THz [1], has opened the window of broader opportunities over economical broadband communication furthermore as biological sensing, drug testing, chemical analysis, astronomy, medical specialty [2], etc. In recent days, scholars put their attention in designing low loss terahertz fibers but the study on bending loss has comparatively lagged. In the applied field, bend losses are a commonly experienced problem in fiber optics and manifest supplementary propagation losses by coupling light from core modes to cladding modes once they are bent. It is essential to assure minimum transmission loss with a very small bending loss in specific applications, like terahertz sensing and medical imaging. Commonly bend losses increased for a longer wavelength and so THz propagation provides shorter wavelength and is very much suitable for where minimum bending loss is required. A. Habib et al. [3] showed a very low bending loss of 5.45×10^{-11} cm^{-1} with a low material loss of 0.07 cm^{-1} at 1 THz frequency. Another article [4] exhibited a low EML of 0.07 cm^{-1} with low confinement loss of $7.2\times10^{-3}\mathrm{dB/cm}$ and low bendng loss of 1.13×10^{-13} at 1.2 THz. Recently, article [5] exhibited a very low EML of 0.03 cm^{-1}, low bending loss of $7.4\times10^{-20}\mathrm{cm}^{-1}$. But this article didn't analyse the power fraction of core. In this manuscript, a hexagonal shaped cladding with octagonal shaped porous-core is presented where the cladding region consists of three-layer air holes. However, this study finds an ultra-low bending loss for a bending radius of 1 cm and 2 cm which has prescribed as a purpose of frequency and core porosity. The bending loss achieved from this design for a 1 cm bending radius is $6.5\times10^{-18}\mathrm{cm}^{-1}$ at 1 THz frequency which is nearly inconsiderable. Besides, a low effective material loss of 0.057 cm^{-1} and ultra-small confinement loss of $5.84\times10^{-5}\mathrm{cm}^{-1}$ has also been reached at 1 THz frequency. Further analysis includes power fraction of core which is found about 42%. The low loss profile of the proposed fiber will make the THZ wave propagation more efficient. The projected PCF is very simple to comprehend and can be fabricated without difficulty with current technology.

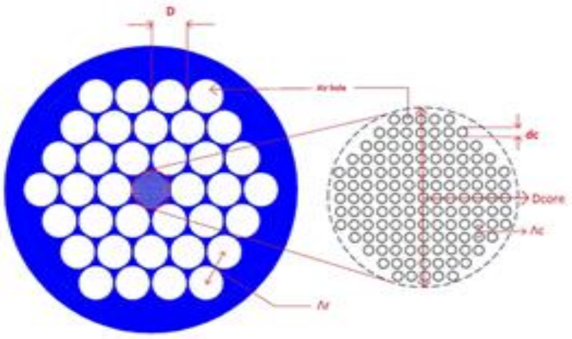

Fig 1:- Cross-section view of the proposed PCF of octagonal-core and hexagonal cladding with an enlarged view of the porous core.

II. DESIGN METHODOLOGY

The graphical representation of the proposed PC-PCF is exposed in fig. 1 associated with a magnified view of the porous core. It seems quite clear from the schematic that the outer cladding air hole forms a hexagonal shape while the inner air hole forms an octagonal structure. The diameter of the inner octagonal core is represented as $\mathrm{D_{Core}}$ as per seen from fig. 1 along with the radius of the cladding air hole and the core air hole is expressed as D and dc correspondingly. Λr and Λc represent the hole to hole distance of the outer region and the inner core respectively.

Throughout this design procedure, a relationship is made between Λr and Λc to $\mathrm{D}_{\mathrm{Core}}$ so that changing in $\mathrm{D}_{\mathrm{Core}}$ can automatically reconcile the inner and outer pitch. These parameters are interrelated by, Λr = $\mathrm{D}_{\mathrm{Core}}/.47$ and Λc = $\mathrm{D}_{\mathrm{Core}}/13$. The parameter dc is also related to $\mathrm{D}_{\mathrm{Core}}$ and denoted as, $d_c = 0.088 \times (\mathrm{D}_{\mathrm{Core}}/2) + (.277 \times \mathrm{D}_{\mathrm{Core}}) \times \sqrt{\mathrm{P}}$, where P represents the percentage of porosity. The highest core porosity accomplished from this design schematic is equal to 68% where above this percentage, air holes in the core get overlapped. More than a few simulations were done to regulate the inner air hole radius and porosity. Throughout this design procedure, a circular perfectly matched layer (PML) boundary conditions are employed in the outer cladding to soak up the nonparticulate radiation motion towards the surface. In this study, the whole PCF is predicated on cyclic-olefin copolymer (COC), that is commercially called TOPAS, for having a stable refractive index of n = 1.53 over 0.1—2 THz [4] and bulk material absorption loss of $\alpha_{mat} = 0.2\ \mathrm{cm}^{-1}$ at f = 1 THz together with alternative blessing such as flat water absorption, high transition temperature for glass, and excellent optical stability after humidity and heat exposure etc. [1].

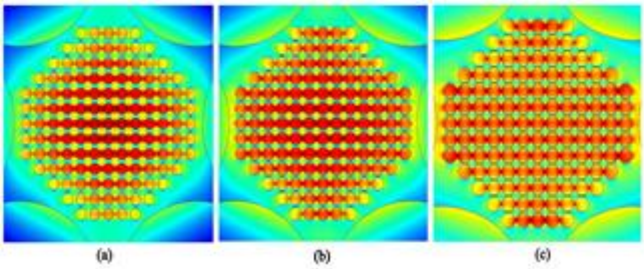

Fig 2:- Mode field distributions of the proposed PCF at porosity (a) 40% (b) 50% and (c) 60% at Dcore = 300 µm and f = 1 THz.

III. SIMULATION RESULTS AND DISCUSSIONS

The finite element method (FEM) was used to simulate the proposed octagonal PC-PCF using software COMSOL version 4.2. An illustration of the mode profiles of the proposed PCF is given in fig. 2. It is clear from the mode profiles that increasing core porosities result in the spreading of light waves towards the outer area since the risen-up porosity shrinks the core area. Light waves experienced several losses when propagating through the fiber due to the characteristics of the waveguide and orientation of the PCF. Confinement loss, effective material loss (EML), and bending loss are most significant among them. The bending loss which is occurred when a fiber undergoes a bending of the finite radius of curvature. During practical implementation, bending loss required to be as low as possible since whenever a fiber cable turns a corner or when fibers are incorporated in cables its experienced bending loss. The formula for determining bending loss is given by [1],

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

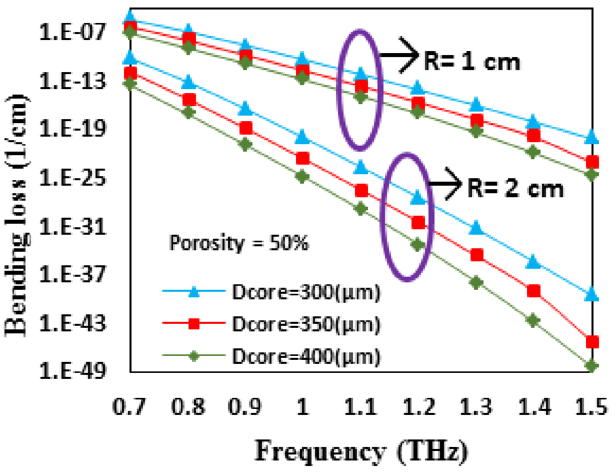

Fig 3:- Bending loss as a function of frequency for different core radius with indicating bending radius R = 1 cm and 2 cm at 50% core porosity.

Where A_{eff} denotes the effective propagating area of the wavelength, R signifies the radius of a bent fiber and $F(x) = x^{-1/2}e^{-x}$. The propagation constant β and β_{cl} are defined as, $\beta = 2\pi n_{co}/\lambda$ and $\beta = 2\pi n_{cl}/\lambda$ correspondingly where n_{co} and n_{cl} denote the refractive index of core and cladding respectively. The value of the effective index of core (n_{co}) can be substituted by the effective index of guiding mode (n_{eff}), ascribed to the porous assembly. Since the cladding is nearly holey compared to core, the value of n_{cl} can be assumed to be 1 [1]. When core diameter is 400 µm , the α_{BL} is $1.51 \times 10^{-13}\mathrm{cm}^{-1}$ and $1.62 \times 10^{-25}\mathrm{cm}^{-1}$ for R= 1 cm and 2 cm correspondingly at 1 THz operating frequency which depicted in fig. 3. It is evident that an increase in the radius of curvature causes a significant reduction in bending loss. The bending loss also decreases for a shorter wavelength that means higher operating frequency as seen from fig. 3, the loss is $3.11 \times 10^{-14}\mathrm{cm}^{-1}$ at 0.7 THz while at 1.5 THz operating frequency the α_{BL} is $5.14 \times 10^{-49}\mathrm{cm}^{-1}$ that indicates about 3.5 times lower bending loss is achieved using a higher frequency. Fig. 4 points out the bending loss for various bent radius as a function of core porosity with a diameter of 300 µm and operating frequency f = 1 THz. With R = 1 cm and porosity 30%, the ultra-low bending loss is found about $6.5 \times 10^{-18}\mathrm{cm}^{-1}$ while for 40% porosity, the loss is $3.58 \times 10^{-14}\mathrm{cm}^{-1}$. It is noticeable that with scaling up core porosity, the magnitude of bending loss increased significantly. The reason behind this is a condition when the diagonal length is fixed, incrementing the porosity of core results in dropping of the index contrast between the area of the core and cladding. Since the index contrast getting reduced, the guiding mode of the core delocalized easily which in turn reduces the bending loss of the PC-PCF structure [1]. A fiber optics cable's efficiency depends much on the status of effective material loss. It occurs when the light wave propagates through the core, part of the wave is consumed by the core material itself. The effective material loss (EML) is often calculated by the following expression [5],

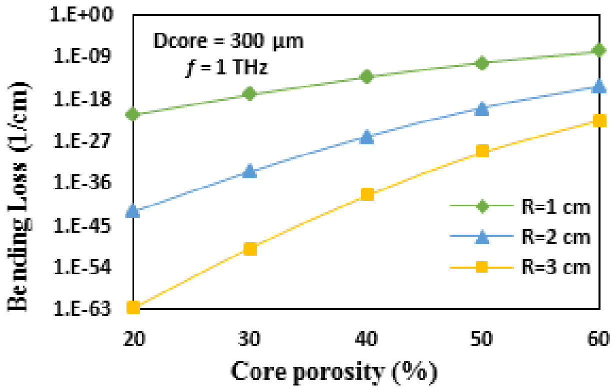

Fig 4:- Bending loss as a function of core porosity for different values of bend radius at D_Core= 300 µm and operating frequency f = 1 THz.

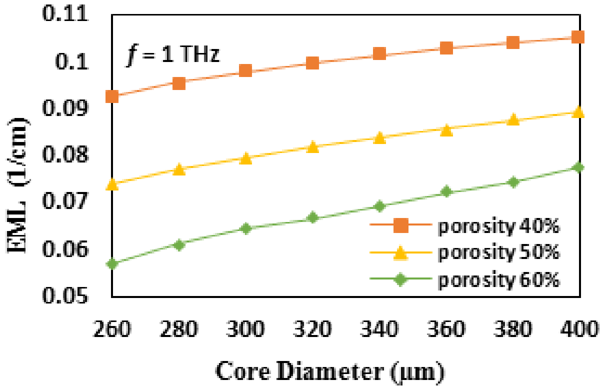

Fig 5:- EML of the proposed PCF as a functon of core diameter with different porosities at operating frequency of 1 THz.

$$\alpha_{eff} = \frac{(\varepsilon_0/\mu_o)^{1/2} \int_{A_{mat}} n\alpha_{mat} |E|^2 \, dA}{2 \int_{All} s_z \, dA} \text{cm}^{-1}, \quad (2)$$

Where ε_o and μ_o indicate the permittivity and permeability constant of vacuum, respectively, n is the refractive index of TOPAS, α_{mat} symbolizes the bulk material absorption loss and E denotes the component of the electric field. The z-component of the Poynting vector is represented as Sz and defined by [2], $s_z = \frac{1}{2}\text{Re}(E \times H^*)_z$, where H^* defines the complex conjugate of magnetic field component. Fig. 5 shows a comparative study of effective material loss of the proposed schematic between different core porosities at the frequency of 1 THz. The value of EML smoothly rises with scaling up the core diameter at a specific porosity. When the porosity is fixed at 60% and f = 1 THz, the corresponding. EML is 0.057 cm^{-1} and 0.0774 cm^{-1} for D_{Core}= 260 µm and 400 µm respectively. This is because when the core diameter rises, the amount of solid material goes up and consequently the material loss gets higher. Again, when the frequency is increasing, the EML rises consequently at a fixed D_{Core} which can be observed from fig. 6. At f = 1.5 THz, EML is 0.0857 cm^{-1} while at f = 0.7 THz, EML reduced to 0.0521 cm^{-1} at 60% core porosity. Furthermore, it can also be evident that at lower porosities EML is higher since the guiding electromagnetic wave interacts with less amount of material.

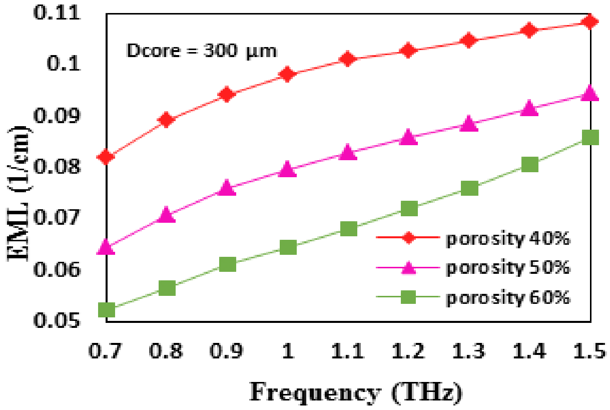

Fig 6:- EML of the suggested PCF as a characteristic of the operating frequency with different core porosities at D_Core = 300 µm.

Since the PCF consists of a non-perfect structure in the core section and for a leaky nature of the structure, some of the traveling waves are trapped by the cladding region, commonly known as confinement loss. This loss can be measured by the following expression [1],

$$\alpha_{CL} = 8.686 \times \frac{2\pi f}{c} Im(n_{eff}) \text{ dB/cm}, \quad (3)$$

Where f is the operating frequency, c is the speed of light and Im(n_{eff}) is the imaginary part of the effective refractive index which was determined in Fig. 7, defines confinement loss with different core porosities ad as a function of operating frequency where D_{Core} is fixed at 300 µm. It is found that, at a fixed frequency of 1 THz, confinement loss is 8.513×10^{-2} dB/cm for 60% while for 40% loss is 5.84×10^{-5} dB/cm. It clearly indicates that the lower the porosity, the lesser the confinement loss and the magnitude is lowest when operating at maximum frequency. Here, the lowest loss achieved is 2.398×10^{-8} dB/cm at 1.5 THz frequency since operating at a higher frequency, mode strength tightly constricts on the porous core region.

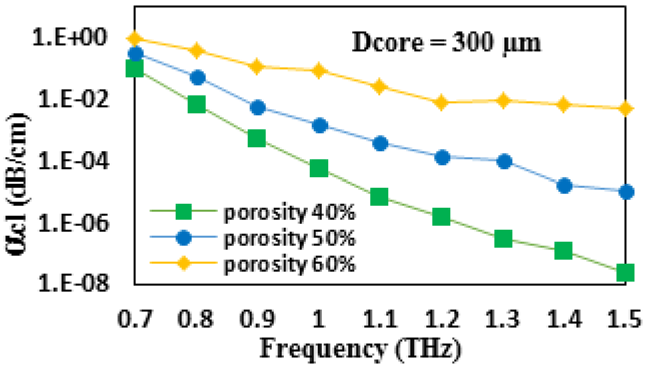

Fig 7:- Confinement loss of the proposed PCF as a function of frequencies for different core porosities at D_Core = 300 µm.

Mode power fraction is an essential parameter that describes the quantity of power that propagates through different areas and may be expressed with the resource of the subsequent expression [4],

$$\text{Power fraction} = \frac{\int_x s_z\,dA}{\int_{All} s_z\,dA}, \qquad (4)$$

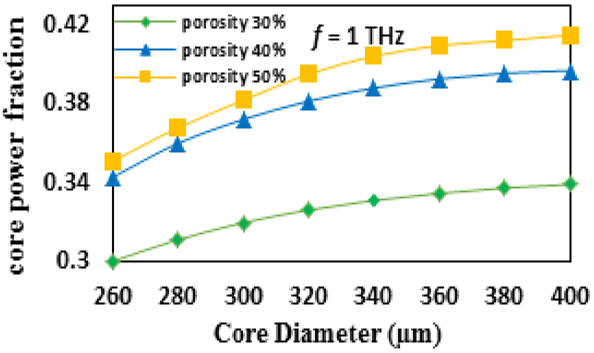

Fig 8:- Power fraction in the core of the proposed PCF as a function of D_Core for different core porosities at f = 1 THz.

Where x within the numerator denotes the area of vicinity of interests and denominator denotes the overall region. Figure 8 represents power fraction in air holes of the porous core as a feature of D_{Core} with three different core porosities at a fixed frequency of 1 THz. Growing the value of core porosity ends in increase the amount of air quantity in the porous-center place and mode power often propagates via it and will increase the power fraction of core air holes. It is found that 42% of power propagates through the core of the proposed schematic at D_{Core} = 400 µm and f = 1 THz where porosity is about 50%. Fabrication feasibility is an important criterion to follow for PCFs and fortunately fabrication precision and accuracy are progressing day by day. Most recently, a well-known sol-gel technique [5] along with capillary stacking technology which is truly feasible and handy for PCF fabrication [5] can be used to fabricate this suggested PCF. A characteristics comparison of the proposed PCF with some recent notable literature is given in table I, which shows the proposed fiber is more promising than those.

Ref.	***f (THz)***	$\boldsymbol{\alpha_{BL}(cm^{-1})}$	$\boldsymbol{EML\ (cm^{-1})}$	$\boldsymbol{\alpha_{CL}\ (dB/cm)}$
[1]	1	–	0.081	–
[2]	1	–	0.04	1.0×10^{-4}
[4]	1.2	1.13×10^{-13}	0.07	7.2×10^{-3}
This Article	1	6.5×10^{-18}	0.057	5.84×10^{-5}

Table 1:- Comparison among the bending loss, EML and confinement loss of the proposed PCF with some recent remarkable designs.

IV. CONCLUSION

In conclusion, we have designed and investigated a new kind of porous-core PCF that contains an octagonal lattice in the core region and hexagonal lattice in the cladding region. It's guiding properties are characterized by different values of core porosities, operating frequency, and core length in the THz frequency spectrum. The proposed PCF exhibits an inconsiderable bending loss of 6.5×10^{-18} cm^{-1} for a tight bend radius of 1 cm. Furthermore, very small EML of 0.057 cm^{-1}, and low confinement loss are obtained for standard frequency range. Moreover, a high-power fraction of 42% is also attained for standard design parameters. Its realistic dimension made it quite suitable for fabricating with the ongoing commercial methods. For having an excellent guiding profile, this proposed PCF can be a decent candidate for THz communications in several fields.

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