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Cyclic Olefin Copolymer Based Photonic Crystal Fiber as Single Mode THz Waveguide

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Abstract: Photonic Crystal Fiber Technology (PCF) based terahertz (THz) communication is widely considered the key component of future generation high capacity communication and biomedical engineering. The most difficult aspect of employing this technology is minimizing material losses and dispersion over longer distances. In PCF modeling, a wide variety of materials are considered (Zeonex, Silica, Cyclic Olefin Copolymer, etc.). The Cyclic Olefin Copolymer (COC) stands out as a highly flexible material that is both easily fabricable and inexpensive. This study proposed hexagonal porous cladding and core using the Finite Element Method (FEM). A fiber with an optimal core diameter of 300 μm, a low Effective Material Loss (EML) of 0.039456 cm^{-1}, a low Confinement Loss (CL) of 2.264×10^{-5} dBcm^{-1}, dispersion of 0.8594 psTHz^{-1}cm^{-1} and V-parameter of 1.42 are obtained for 1 THz operating frequency. The suggested fiber's propagation parameters have been diligently analyzed and obtained promising values. A significant porosity of 65% and power fraction of 29.88% was recorded.

Keywords: Birefringence, Effective Material Loss (EML), Photonic Crystal Fiber (PCF), THz Guidance, Confinement Loss (CL), Cyclic Olefin Copolymer (COC).

1. Introduction

Collaboration between scientists, researchers and engineers in the realm of technology and scientific analysis is rapidly evolving. Terahertz (THz) radiation has already made significant strides in this sector. Photons with an energy of 1-100 meV is able to pass through materials that would be non-transparent to visible light and this band of energy is vital for many different optical applications such as laser, mirror, fiber optic, microscope lens, etc. It provides greater bandwidth than the microwave frequency range. Because low-frequency microwave radiation has a limited transmission range. Broadband photonic materials for the THz bandwidth has enabled light wave interaction experiments, revealing new aspects of advanced physiology, solid-state, and basic electromagnetic phenomena [1], [2], [3]. THz radiation provides the high-speed communication possible. This technology uses less power, which increases communication performance and stability. So, for better and more reliable communication, low-loss fiber is a necessity. To ensure optimal THz communication, PCF is the forthcoming generation waveguide in which holes are strategically inserted inside the core and cladding regions based on selected geometry. Numerous different properties are exhibited by the holes depending on their size and shape and as a consequence, there are numerous applications for them. In addition, the PCF behaviors are affected by the light guiding method.

According to the light guidance method, two fundamental types of PCF exist: (i) Index Guiding and (ii) Photonic Band Gap. Index Guiding (IG) is a method of directing light that relies on total internal reflection. Since the core's effective refractive index is so small in Photonic Band Gap (PBG) components, the propagation technique of a transmitted fiber is highly dependent on the band gap phenomena. Despite the fact that THz is a pretty recent region of study, there are numerous applications such as neuroimaging and detection. THz beams having a wide depth of focus can be employed in THz imaging [4], also THz spectroscopy can be applied to identify the conformational condition of molecules in fluids [5][6]. Designing a THz waveguide with low transmission losses could be challenging. As a result of this, scientists and engineers have published certain significant research publications. According to the study conducted by Hasan et al. [7] the developed PCF presents an EML 0.076 cm^{-1} at 1.0 THz. This finding suggests a substantial reduction of approximately 62% in the background material's overall loss due to absorption. Furthermore, the fiber under consideration demonstrates a low level of confinement loss, specifically 8.96×10^{-3} dBcm^{-1}, as

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well as a low and consistent flattened dispersion of 0.96 ± 0.086 $psTHz^{-1}cm^{-1}$, which is achieved by the ideal design parameters. In addition to the aforementioned factors, the investigation also encompasses a comprehensive analysis of other significant propagation features, including single-mode propagation and bending loss. Also, their another study [8] introduces a PCF that incorporates a core with the shape of a rhombus composed of round air holes within the usual cladding that is hexagonal. This design enables the achievement of an exceptionally minimum bending loss 3.04×10^{-11} cm^{-1} at 1 THz. Furthermore, optimal design parameters result in a low EML 0.089 cm^{-1} and a minimal CL 1.17×10^{-3} $dBcm^{-1}$. The fiber under consideration exhibits highly favorable wave-guiding characteristics, making it a highly interesting candidate for applications in terahertz imaging and flexible communication. Rana et al. [9] introduce a newly developed pointed core fiber that incorporates a pointed cladding specifically designed for THz spectrum. The numerical investigation of the modal parameters of the planned fiber is conducted using FEM approach. The results of the simulation reveal an absorption loss ranging from 0.0103 to 0.0145 cm^{-1}, as well as a low dispersion below 0.5 $psTHz^{-1}cm^{-1}$ at 0.5–0.9 THz frequency. According to Islam et al. [10] a polarization sustaining PCF utilizing Topas as the foundation material. This PCF exhibits very low EML and nearly zero flattening dispersion qualities, enabling efficient transmission of terahertz waves while conserving their polarization. They used FEM in conjunction with a PML boundary condition. The findings ensure a lower EML value of 0.034 cm^{-1}, a reduced CL value of $10^{-3.7}$ cm^{-1}, an effective mode area of 0.6×10^6 μm^2 which is higher and a variation of dispersion of 0.09 $psTHz^{-1}cm^{-1}$. In order to streamline the manufacturing procedure, the utilization of exclusively round air holes with a hexagonal cladding is implemented. Slotted core and circular Kagome PCFs are proposed by Asaduzzaman et al. [11]. Numerical analysis is employed to investigate the application of a broad frequency range spanning from 0.8 THz to 2 THz. The research introduces two Kagome photonic crystal fibers (PCFs) with distinct core structures, thereby contributing to the existing body of knowledge in this field. The first kind is characterised by a slotted core based on elliptical and rectangular shaped hole, while the second type features a round-shaped hole in a hexagonal core. The optical properties of photonic crystal fibers (PCFs) were examined by varying their geometry. The PCF offers several notable advantages, including improved performance in dispersion, birefringence, confinement loss, effective material loss and V-parameters. In another research Asaduzzaman et al. [12] proposed a PCF that has the cladding with umbrella shape and the core that is slotted. The focused PCF was systematically investigated across a wider frequency range of 0.8 to 2.4 THz. A combination of elliptical and rectangular shaped holes are organized in the core. The backdrop material used in this investigation was COC. The polarization-maintaining PCF exhibits a significantly high level of birefringence, measuring 6.10×10^{-1}. It also demonstrates a low level of confinement loss, measuring 3×10^{-9} dBm^{-1}, as well as a low EML of 0.129 cm^{-1}.

This study aimed to propose a porous core PCF that minimizes optical fiber communication losses (EML, CL) and Dispersion to increase the long-distance transmission data rate. At frequency 1 THz, it generates the highest birefringence. The proposed material has a refractive index of 1.531 which is dependent on the polarization and direction of light propagation in the waveguide and shows optical birefringence properties [13]. To calculate the optimum confinement loss, the model is computed using the FEM method with a Perfectly Matched Layer (PML) outside the core. A hexagonal PCF with circular air holes in the fiber cladding is proposed here. The holes have a circular shape. Throughout this scenario, a lattice with a hexagonal shape having ellipse-shaped holes has been applied. Furthermore, it operates as a single-mode fiber throughout the entire tested frequency band and makes it suitable for low-loss THz pulse guiding. When the cladding and core had the same shape, confinement loss (CL) was relatively larger, but it was smaller when the shapes were different. As a result, CL which can be obtained based on the diameter, pitch and shape of perforations, was greatly reduced in the proposed design by adopting hexagonal shapes for both the cladding and the core. We conducted a thorough analysis of these characteristics and were able to decrease transmission loss, enabling more rapid and longer transmission. The proposed optimum fiber structure design may work as ideal alternative for the available communication method as compared to the present low-loss waveguide. The major findings of this study are as follows:

- A significantly low EML of 0.039456 cm^{-1}.
- A very low Confinement Loss of 2.264×10^{-5} $dBcm^{-1}$.
- A high porosity of 65%.

Methodology has been described in section 2, Device Structure and Design are described in section 3, Results and Discussions are described in section 4 and at the end Conclusion section has been added to summarize the key research findings.

2. Methodology

A fiber-optic cable is a light-carrying structure that appears like an electrical cable but contains one or more optical fibers. Individually coated optical fiber components are normally placed in a protective tube adequate for the environment. Fiber optics are made up of an inner core and a cladding layer on the outside. Because of the difference in refractive index, the inner core is chosen for total internal reflection. The fiber's area is mainly composed of holes and has been distributed throughout the fiber structure according to the following two equations [14]:

$$x = aLcos(\frac{2\pi n}{LT}) \quad (1)$$

$$y = aT\,sin(\frac{2\pi n}{LT}) \tag{2}$$

The lattice constant, the ring's terminal number and the number of the elements from 1 to $L \times T$ are each denoted by the values of a, L and n respectively. T refers to the hole number in the first ring of the cladding area. An independent ring in the cladding area contains $L \times T$ holes, which are arranged in a circle. Angular distance is calculated using the equation $\theta = 360° \div (L \times T)$, where $L=$ first, second, ..., seventh; ring of holes. The angular difference between two adjoining holes in the same ring is measured. Effective Material Loss (EML) significantly reduces as the hole size increases with core confinement. To design the proposed model, FEM has been used. A fine mesh was added in this model to improve accuracy. To calculate confinement loss, a new layer called the PML was added outside the core. Due to its constant refractive index 1, dry air has been assumed and as a consequence, the absorption loss has been reduced to almost zero. This work also analyses power fraction, loss due to dispersion and the Normalized frequency (V-parameter).

The EML of a proposed photonic crystal fiber can be determined using the following equation [14]:

$$a_{eff} = \sqrt{0.0000070426}(\frac{\int_{mat} n_{mat}|E|^2\alpha_{mat}dA}{|\int_{all} s_z dA|}) \tag{3}$$

Where 0.0000070426 is the ratio of vacuum permittivity and permeability ($\frac{\varepsilon_0}{\mu_0}$), n_{mat} is the refractive index of the proposed model. The electric field is defined as E, α_{mat} is defined as the bulk material absorption loss and S_z is the pointing vector of the z-component [14]:

$$S_z = \frac{1}{2}(E \times H) \cdot z \tag{4}$$

Where the electric and magnetic fields are represented by E and H, respectively.

Confinement loss is typically calculated based on the amount of material contained inside the core and is expressed as [14],

$$\alpha_{CL} = 8.686 k_0 I_m(n_{eff}) \tag{5}$$

Where k_0 (Wave number) is a proportionality constant. $k_0 = \frac{2\pi}{\lambda}$ and $I_m(n_{eff})$ are imaginary parts of the refractive index.

The equation for determining the level of dispersion is as follows [15]:

$$D(\lambda) = -\frac{\lambda}{C(\frac{d^2 R_e(n_{eff})}{d\lambda^2})} \tag{6}$$

Where $Re(n_{eff})$ is real part of effective refractive index (n_{eff}), λ is the wavelength in vacuum, C is the light velocity in vacuum.

The formula for determining normalized frequency (V-parameter) is [16]:

$$V = \frac{2\pi rf}{C}\sqrt{n_1^2 - n_2^2} \leq 2.405 \tag{7}$$

Where r is the core radius and C is the vacuum speed of light. n_1^2 and n_2^2 are the refractive indexes of core and cladding respectively. $V \leq 2.405$ condition is for single mode communication.

3. Device Structure and Design

The most important aspect of every optical fiber is its design and material composition. As previously mentioned, fiber optic cables are composed of three components: a core, a cladding and a coating. The light-transmission medium of the optical fiber is core, which is made of either glass or plastic. The cladding material is designed to have a low refractive index at the interface with the core, which induces internal reflection within the core. Light waves are confined inside the fiber as a result of this configuration. In order to keep the strength of the material, absorb energy and shield the core and cladding, fiber optic coatings are typically coated with multiple layers of plastic. The suggested structure can be established via the following conventional procedure.

In order to simplify the fabrication complexity, a hexagonal PCF with the cladding having circular air holes is proposed here. The air-hole diameter is 2.6 μm and the hole pitch is 5.6 μm. In comparison with the regular shape,

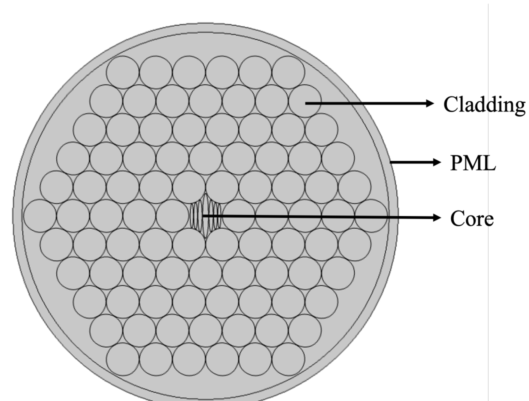

Figure 1. Design of the proposed photonic crystal fiber (PCF).

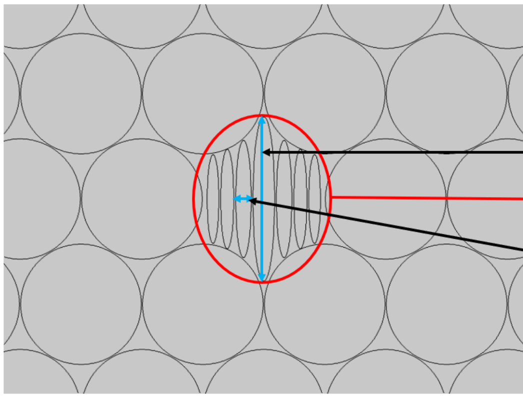

Figure 2. Cross-sectional diagram of the proposed hexagonal core.

the hexagonal shape occupies an area with equal-sized air holes and leaves no wasted space. Figure 1 and Figure 2, provides a cross-sectional perspective of the PCF according to investigation. The core is a hexagonal lattice with elliptical shaped holes inside it. D_{core} is the abbreviation for the overall width of the core. Here, d_x and d_y are the diameters of the primary and secondary axes of the air holes. This proposed design was simulated by varying the value of d_x while maintaining the constants D_{core}, d_x and total radius of the fiber = $Core/A$ [17]. A is the area. Inside the core, there are 7 ellipse-shaped holes of different size diameters to get high birefringence. In this fiber model, air holes were employed instead of gas ones. To analyze the proposed model's optical confinement loss, a PML is designed beyond the cladding.

Our simulated PCR model can be fabricated using a special kind (copolymers of styrene-divinylbenzene) of polymer porous fiber. A hexagonal structure PCF has been designed through using holes which are perfectly circular in size. Cyclic Olefin Copolymer (COC) was used to design THz waveguiding. The low bulk absorption loss of COC at 1 THz makes it highly popular [18], [19], [20], [21], [22]. The transmission properties of the suggested fiber model were analysed using the full-vector FEM. The refractive index n of COC in the THz spectrum remains constant at a value of 1.531.

In this model, silicon dioxide (SiO_2) has been used in the core, because it has a number of highly desirable characteristics, including a broad wavelength range with good optical transparency and high-temperature stability. Furthermore, by employing SiO_2 in the core, the output has a low EML and a low CL [23]. Because most of the light propagation occurs within the core, SiO_2 preserves the core from melting and allows it to last for a longer time which makes it particularly reliable in industrial uses. The multi-hole SiO_2 capillaries for optical fiber fabrication are made with silica glass using the slurry casting method [24]. As a starting material, highly pure SiO_2 powder need to be used, which can be manufactured by thermal oxidation of silicon chloride ($SiCl_4$). Ball milling needs to be used to combine a sufficient supply of distilled water, an organic glue, a dispersion solvent and SiO_2 powder. The polymer solution needs to be poured into a metal mold after making it. To create holes in the genuine design, stainless wires of the required diameter should be inserted into the mold. It is well known that different PCF designs can be created based on wire size and geometry. After the glue has dried completely, the wire needs to be detached, as well as the preform from the mold. After that, the dry preform needs to be calcined to remove organic impurities using high-temperature oxidation. The calcined preform can be purified to eliminate metallic contaminants before sintering at 1500°C (1773.15 *kelvin*). The production of a transparent preform of PCF silica glass can be achieved through the process of sintering the preform in a dry state. The preform is carefully inserted into the optical fiber, ensuring that the tension in the holes is consistently maintained. This process is carried out to achieve a uniform and homogeneous microstructure in the photonic crystal fiber (PCF). The PCF illustration process must be conducted at a temperature of 1950°C (2223.15 *kelvin*) at a speed of 100 m/min. In the closed air-hole drafting system, it is necessary to connect simulated SiO_2 rods at both ends of the preform for photonic crystal fiber (PCF) in order to effectively seal the holes. The attachment of one end of the photonic crystal fiber (PCF) preform to the SiO_2 tube is required, while the other end should be connected to a silica rod.

The transmission loss is partially dependent on the structured design. So, it is essential to be aware of the fabrication accuracy.

4. Results and Discussions

Following the design of an optical fiber, the next most important step is computation. The loss would vary depending on the configuration of the optical fiber, even. though fiber has a low transmission loss, it would be quite efficient being used in short-distance high-speed communication.

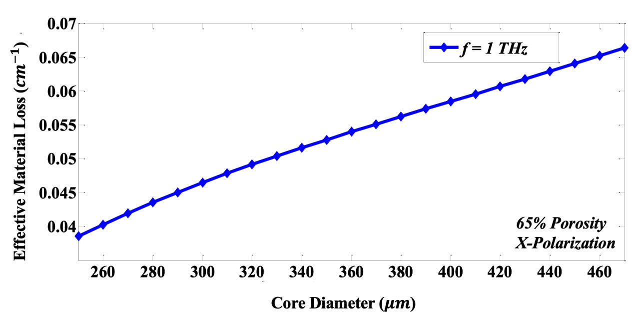

Figure 3. Effective Material Loss (EML) Vs Core Diameter at 1 THz.

The most essential guiding feature of a THz waveguide is EML. The EML value represents the total quantity of light energy absorbed by the composite. The core diameter has been varied to observe the EML at 1 THz and is represented in figure 3. The core diameter is proportionally correlated with the EML in this graph and almost increases linearly. Porosity measures the number of fluids bearing voids or pores present in a given soil formation. Checking the porosity from 40% to 70%, we found the optimum porosity value (65%). So, the lowest EML 0.039456 cm^{-1} was calculated at a porosity of 65% in the X direction. The diameter of the core was increased from 250 to 470 micrometers. This graph indicates that the EML is proportional to core diameter so keeping the diameter of the core low (300μm) is a priority to get the optimum EML.

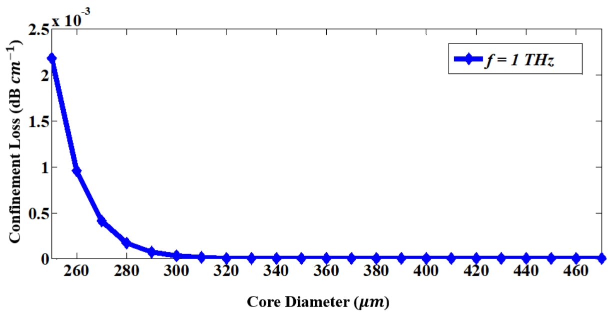

Figure 4. Confinement Loss Vs Core Diameter at 1 THz.

Confinement loss is an essential element to examine while developing a PCF. Figure 4 shows that as core diameter rises, the confinement loss decreases. However, after the value of core diameter reaches 300 μm, it began to be negligible. As previously we have seen in Figure 3 that the EML increases proportionally to core diameter, so for keeping the value of EML minimum, the proposed signal's confinement loss at 1 THz is calculated as 2.264×10^{-5} $dBcm^{-1}$ at the core diameter of 300 μm.

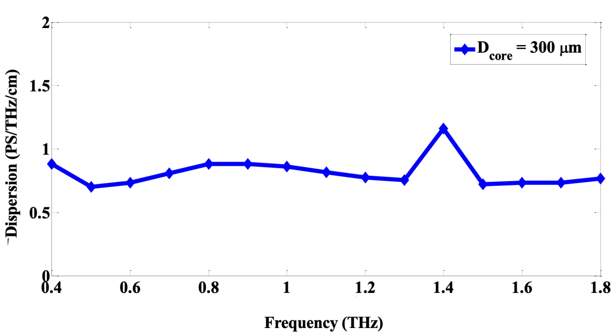

Figure 5. Dispersion Vs frequency at 300 μm core diameter (D_{core}).

Figure 5 illustrates the relationship between dispersion loss and frequency. Here, the frequency of the signal is increasing, while the dispersion loss is fluctuating. Because it allows numerous optical signals with almost equal pulse spreading to be transmitted simultaneously, lower dispersion loss is required for each PCF enabling transmission efficiency. The maximum level of dispersion is seen at 1.4 THz frequency. Since the dispersion is nearly flat around this frequency (up to 1.3 THz), optical multiplexing with flat dispersion is possible in this frequency range. The dispersion loss of our proposed fiber is 0.8594 $psTHz^{-1}cm^{-1}$ at 1 THz.

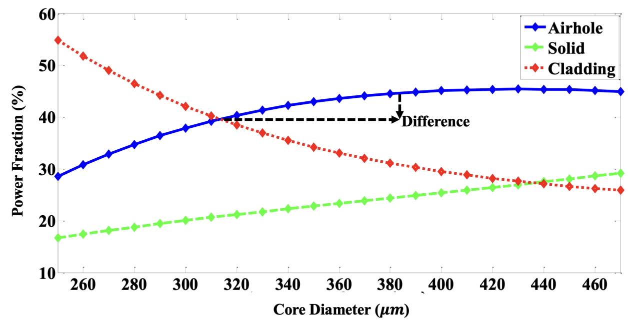

Figure 6. The power fraction of the airhole, sold and cladding in proportion to the diameter of the core.

The power fraction can be used to estimate the quantity of light that travels through the cladding and core regions shown in figure 6. The magnitude of a number is expressed as a power fraction. Almost 39.88% of light is propagating in the air hole. The power portion was evaluated in the hole of the porous core. The graphic clearly shows that raising the core porosity enhances the power fraction in air-core holes. Light travels through the solid substance (core material) at a rate of 18.04%, while it travels through the cladding air at a rate of 42.08%. The maximum air hole power fraction value is approximately after 380 μm. However, while this 380 μm core diameter would have the same confinement loss, but it would greatly increase the EML, which is a significant issue. Figures 3 and 4 reveal that if the core diameter is greater than 300 μm, the EML increases and if it is less than 300 μm, the confinement loss increases. Since the EML and confinement loss are both satisfactory at 300 μm, this core diameter was chosen as the optimal for power fraction and V-parameter in this study.

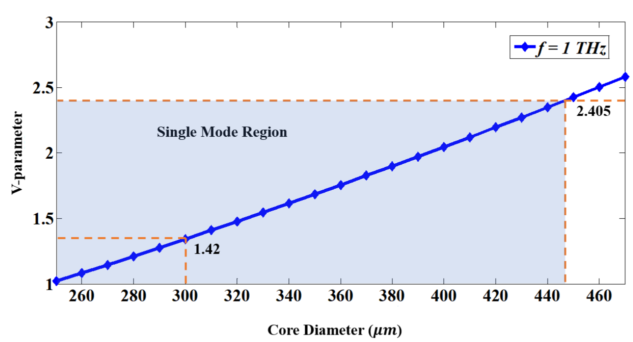

Figure 7. V-parameter Vs diameter of the core at 1 THz.

Figure 7 depicts the fluctuation of normalized frequency V with respect to different core diameter values. The values of the V-parameter increase linearly as the core diameter increases. In this particular incident, 1 THz frequency was chosen. Under these conditions ($V < 2.405$ single mode), the range of V-parameter visibility is from 240 to

TABLE I. Comparison of proposed model with the previous studies

	EML (cm^{-1})	CL ($dBcm^{-1}$)	Cladding	Material	Core
Ref [7]	0.076	8.96×10^{-3}	Square	COC	Square
Ref [8]	0.089	1.17×10^{-3}	Hexagonal	COC	Rhombic
Ref [9]	0.0145	3.6×10^{-2}	Rectangular	COC	Rectangular
Ref [10]	0.01	1×10^{-3}	Hexagonal	COC	Rectangular-Triangular
Ref [11]	0.232	2.76×10^{-10}	S-Kagome	COC	Hexagonal
Ref [11]	0.0746	2.98×10^{-9}	C-Kagome	COC	Hexagonal
Ref [12]	0.129	3×10^{-11}	Umbrella	COC	Slotted
Proposed	0.039456	2.264×10^{-5}	Hexagonal	COC	Hexagonal

447 micrometers, hence the diameter of 300 micrometers satisfies the single-mode communication condition. The V-parameter of our proposed fiber is 1.42.

Table I presents a comparison between some previous research studies and the one which is being proposed. These studies used COC as the background material and 1 THz as the frequency. Using the same shape (square, rectangular) both in the cladding and the core normally resulted in comparatively higher confinement loss (CL) in the research [7] [9] and different shapes ended up in lower confinement loss (CL) in the research [8] [10] [11] [12]. The proposed model incorporates a hexagonal structure for both the cladding and the core, leading to a notable decrease in CL and EML. The reduction is accomplished by a calculation of appropriate parameters, including the diameter, pitch and shape. Even though [11] and [12] obtained a lower CL, their EMLs are higher than the proposed model. The approach described above achieved a significantly lower EML of 0.039456, which is essential for faster and longer-distance transmission. A hexagonal shape PCF cannot have any unnecessary gaps, and if there are any, they are barely noticeable, therefore no material loss has occurred. Despite the circular air holes, the proposed porous fiber can be created via assembling or drilling preforms. However, this approach cannot be used easily to create air holes of various forms such as Square, Rhomboid, Rectangular and so on. It is very costly and time consuming. In addition, this proposed model is performing superior with respect to other researchers' output.

A minor limitation of our paper is that confinement loss cannot be reduced beyond 300 μm for certain parameters. If confinement loss can be decreased, transmission speed over vast distances will increase. More favourable outcomes will depend on the wave number, material type and frequency that will be analyzed in future research.

5. Conclusion

In this study, a PCF with hexagonal-shaped cladding and a hexagonal-shaped core has been proposed. To achieve a high birefringence, seven ellipse-shaped holes of varying diameters are located within the core. By applying 1 THz frequency, the proposed model has achieved a significantly lower EML of 0.039456 cm^{-1} and a minimum CL of 2.264 x 10^{-5} $dBcm^{-1}$, which is quite significant for a COC based PCF model. COC has been employed as the background material because it is flexible, can be easily fabricated and is highly advantageous for commercial purposes. In addition, by utilizing SiO_2 in the core, the output has a low EML value and a low CL value. As the maximum propagation of light occurs within the core, SiO_2 prevents the core from disintegrating and extends its lifespan, making it particularly reliable for industrial applications. Additionally, research on a more optimized model is underway by structural adaptation and modification to further reduce the value of CL and Dispersion utilizing various other materials.

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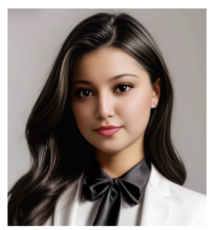

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