Research Article

Analytical approach for modeling and simulation of photonic crystal fiber based on low effective material loss

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Abstract
COMSOL Multiphysics simulation software has been used to create a hexagonal photonic crystal fiber (H-PCF) with hexagonal cladding and a rotating hexa elliptical shape core. The hexagonal photonic crystal fiber (H-PCF) fiber is built on five layers of circular air holes, and it is suitable for telecommunication applications especially optical fiber communication in the terahertz (THz) frequency range. The hexagonal photonic crystal fiber (H-PCF) is designed to have an ultra-low effective material loss (EML), a higher core power fraction, a bigger effective area, and reduced confinement loss. The smallest effective material loss from the proposed hexagonal photonic crystal fiber (H-PCF) is 0.00689 cm^{-1}, with a better core power fraction of 82%, less confinement loss of 3.45×10^{-14} cm^{-1} and a better effective area of 3.65×10^{-4} m^2 is achieved at one terahertz (THz) waveguide region. Furthermore, using the features of the V-Parameter, our developed hexagonal photonic crystal fiber (H-PCF) fiber reveals an optical waveguide with one mode throughout a frequency range of terahertz (THz) wave area. So, it has been said that our hexagonal photonic crystal fiber (H-PCF) structure will be highly beneficial for optical fiber communications applications in the THz frequency range.

Article Highlights

- Analytical approach for modeling and simulation-based photonic crystal fiber based on low effective material loss (0.00689 cm−1)
- Provide 82 percent core power fraction and confinement loss with 3.45x10-14 cm−1
- Competent transmission of broadband hexagonal photonic crystal fiber (H-PCF) THz signals for communication purposes

Keywords PCF · Modeling · THz · EML · Confinement loss · V-parameter · Simulation Work · Scattering loss

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1 Introduction

Photonic Crystal fibers (PCF) are noble type optical fibers where in a microstructure arrangement of different background materials that have different refractive index is present and that microstructure arrangement is periodic. Also, photonic crystal fibers are composed of an air-filled core, capillaries, decided to create several lattice structures. In recent time, the usage of photonic crystal fibers exceedingly because of its unprecedented and unparalleled noble qualities that is not possible with traditional fibers. Although the conventional optical fibers can useful in case various applications, including telecommunication and non-telecommunication, they are not suitable for other significant applications due to its structural and cut-off wavelength limitations and also the materials choice for conventional optical fibers are limited. Therefore, the conventional optical fibers are not so much applicable for wide range of applications. On the contrary, photonic crystal fibers (PCFs) can able to guide light through the fiber using total internal reflection as well as photonic bandgap (PBG) effect [1]. Therefore, photonic crystal fibers are using in various diversified applications both in telecommunication sectors and non-telecommunication sectors.

Researchers have discovered that photonic crystal fibers (PCFs) perform far better than conventional fibers in the terahertz (THz) frequency range. Terahertz (THz) frequency waveguides have been utilized in a variety of applications in recent years, including communication and chemical detection [2], medical imaging [3], spectroscopy [4], astronomy [5], sensors [6], data transmission [7], security screening [8], radio [9] and other diversified applications.

Previously many researchers designed various types of photonic crystal fibers (PCFs) [10] based on different core structures which are designed for terahertz wave regions [11, 12]. Many researchers have used bulk materials for optical waveguides such as ZEONEX [13] and TOPAS [14]. Researchers are drawn to photonic crystal fibers (PCFs) because they produce reduced confinement loss, larger effective area, lower effective material loss (EML) and a greater core power fraction, lower scattering loss, and lower dispersion loss.

Many researchers around the world designed and developed photonic crystal fibers (PCFs) of various structures using terahertz (THz) waveguides. A simple designed of circular photonic crystal fibers is designed by S. Kumar et al. [15] which shows a very lower confinement loss and a negative dispersion rate. Porous core octagonal photonic crystal fibers (POPCFs) for low loss THz frequency region are proposed by S. Kaijage [16]. In their proposed PO-PCF the TOPAS was considered as the background material. Although in their proposed porous core octagonal photonic crystal fibers they found the effective material loss (EML) of 0.07 cm^{-1} but in their proposed PO-PCF they didn't consider two important characteristics parameters such as core dispersion rate and core power fractions. Bao et al. [17] found a higher effective material loss of 0.31 cm^{-1} from their proposed honeycomb bandgap fibers (BGF). Islam et al. [18] presented a hybrid-core circular cladding photonic crystal fiber with ultra-low effective material loss (EML) and ultra-flattened dispersion rate of 0.035 cm^{-1} and 0.07 ps/THz/cm, respectively, for the THz frequency. Hasanujjaman et al. [19] developed and evaluated a porous-core kagome lattice photonic crystal fiber (PCF) that may be used in the Terahertz waveguide. TOPAS was utilized as the background material in their suggested created PCF, and the developed technique of PCF was done using the finite element method (FEM). From their designed PCF the observed an effective material loss (EML) of 0.035 cm^{-1}, lowers confinement loss, and a more stable dispersion loss at 1 terahertz (THz) frequency region.

In our research work, a design of a hexagonal photonic crystal fiber (H-PCF) fiber based on a unique hexagonal from exterior and a core with a rotating hexagonal shape is done where the five layers circular air hole-based hexagonal photonic crystal fiber (H-PCF) fiber is perfect for telecommunication related application specially in optical fiber, laser injection in the terahertz (THz) frequency region. The designed hexagonal photonic crystal fiber (H-PCF) presents an ultra-low effective material loss (EML), It is possible to achieve a higher core power fraction, a lower confinement loss, and a larger effective area. Form the designed hexagonal photonic crystal fiber (H-PCF), the minimum effective material loss (EML) is 0.00689 cm^{-1}, a better core power fraction of 82%, a lower confinement loss of 3.45×10^{-14} cm^{-1} and a better effective area of 3.65×10^{-4} m^2 is achieved at 1 terahertz (THz) waveguide region. The characteristics value that we found with our designed hexagonal photonic crystal fiber (H-PCF) shows much better results than the PCF structure that was previously constructed and described in the articles presented in Table 1.

The article is organized as follows: Sect. 2 describes the design approach of the H-PCF fiber. The mathematical equations and formula that are used in the article is described in Sect. 3. In Sect. 4, the simulation results and outcomes of the model are presented. Finally, the conclusions are outlined in Sect. 5.

Table 1 Comparison table of previously proposed PCF and our proposed H-PCF by examining the characteristics of EML, core porosity, Core Power Fraction, Confinement Loss, Effective Area at 1 THz

Refs	Frequency (THz)	EML (cm^{-1})	Porosity (%)	Power fraction	Confinement loss (cm^{-1})	Effective area [A_{eff} (m^2)]
[26]	1	0.100	30	–	1.0×10^{-01}	2.3×10^{-07}
[27]	1	0.089	60	37%	1.0×10^{-02}	9.77×10^{-08}
[28]	1	0.076	80	53%	8.96×10^{-01}	–
[29]	1	0.038	74	56%	2.35×10^{-01}	6.75×10^{-05}
[30]	1	0.110	–	–	–	0.98×10^{-07}
[31]	1	0.027	85	83%	1.0×10^{-02}	9.48×10^{-08}
[32]	1	0.068	50	–	–	–
[33]	1	0.050	60	42%	1.00	–
[34]	1	0.07	30	–	1.14×10^{-3}	1.07×10^{-9}
[35]	1	0.05	–	67%	7.79×10^{-12}	2.00×10^{-5}
[36]	1	0.078	30	–	1.39×10^{-4}	–
[37]	1	0.043	81	47%	1.00×10^{-2}	2.15×10^{-5}
Proposed H-PCF	1	0.00689	82	82%	3.46×10^{-14}	3.65×10^{-4}

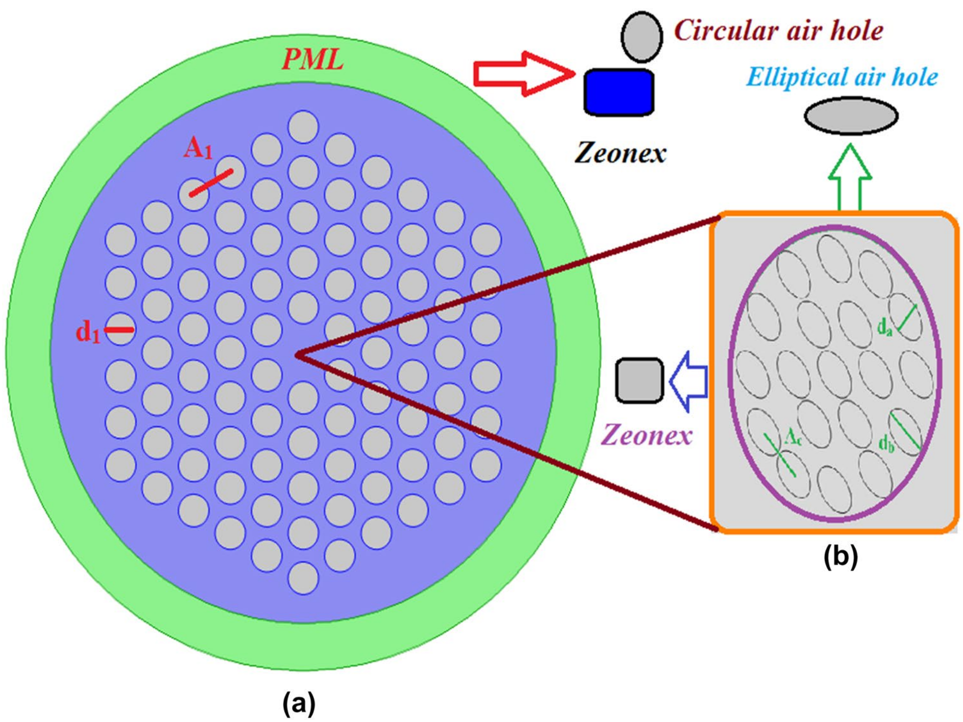

Fig. 1 The views of H-PCF fiber with (**a**) Hexagonal cladding region and (b) Rotated-hexa elliptical core region

2 Approach of design methodology

The hexagonal 5 layers cladding areas with a core region that is rotated hexagonally are shown in Fig. 1. The backdrop material is ZEONEX (n = 1.509), and the rotated-hexa core features elliptical-shaped air holes. This fiber is designed for use in the terahertz (THz) frequency range. The Λ_1 and d_1 parameters specify the cladding area is round air holes pitch and diameter. Furthermore, the initial layer of 6 circular air holes in the elliptical form of the rotated-hexa in core areas. Furthermore, the d_a (width), d_b (height) parameters represent the elliptical form is diameter and pitch Hexagons in rotation are indicated by the Λ_c consistently. ZEONEX (n = 1.509) is utilized as background material to decrease material loss, CL, and SL in terahertz (THz) frequency. Moreover, the thickness of the Perfectly Matched Layer (PML) is calculated by the 8% of the maximum fiber diameter and the optimum parameters are cladding diameter $d_1 = d_2 = d_3 = d_4 = d_5 = 284$ µm, cladding pitch $\Lambda_1 = \Lambda_2 = \Lambda_3 = \Lambda_4 = \Lambda_5 = 375$ µm, core diameter $d_a = 62$ µm, $d_b = 192$ µm, and core pitch $\Lambda_c = 100$ µm and $PML_1 = 2260$ µm and $PML_2 = 2460$ µm.

3 Mathematical data analysis

A general goal Advanced numerical methods are used in COMSOL Multiphysics simulation software. We utilized COMSOL software to build our H-PCF and to numerically analyze it using the Perfectly Matched Layer and Finite Element Method (FEM), calculating all the data the for the numerical study of photo-sensitive comportment.

The calculation of Scattering Loss of H-PCF fiber is done utilizing the following equation [20]:

$$\alpha_R = C_R \times \left(\frac{f}{c}\right)^4 (\text{dB/km}) \tag{1}$$

Here, α_R represents scattering loss, C_R indicates scattering coefficient and a constant value of $C_R = 1$, f is the frequency and c are the speed of light in m/s.

The confinement loss is calculated with the help of the following equation [21]:

$$L_c = 8.686\left(\frac{2\pi f}{c}\right) \text{Im}\left[n_{eff}\right] \times 10^{-2}\text{cm}^{-1} \tag{2}$$

Here, L_c indicates confinement loss, $\text{Im}\left[n_{eff}\right]$ indicates imaginary part of the effective refractive index, f is the functional frequency, c is the speed of light.

Our H-PCF was created with ZEONEX (n = 1.509) as the backdrop material, which absorbed frequencies from our H-PCF. The use of ZEONEX (n = 1.509) material as a backdrop material results in extremely low effective material loss (EML). In order to determine the effective material loss (EML) of our H-PCF design, use the following equation [22]:

$$\alpha_{eff} = \sqrt{\frac{\varepsilon_0}{\mu_0}}\left(\frac{\int_{mat} n_{mat|E|^{2\alpha_{mat}}} dA}{\left|\int_{all} S_z dA\right|}\right)(\text{cm}^{-1}) \tag{3}$$

Here, α_{eff} represents the EML of H-PCF, μ_0 is the permeability in comparison, ε_0 represents the relative permittivity, n_{mat} is the refractive index, S_z indicates the pointing vector, $\alpha_{mat} = 1$ is the absorption loss. A pointing vector is shown by the following relation:

$$S_z = \frac{1}{2}\left(E \times H^*\right)$$

Using the following equation as a guide the effective area can be calculated [23]:

$$A_{eff} = \frac{\left[\int I(rd) rddrd\right]^2}{\left[\int I^2(rd) drd\right]^2} (\text{m}^2) \tag{4}$$

where, $A_{\text{eff is the}}$ effective area, I (r) is the cross-sectional electric field intensity and $I(rd) = |E_t|^2$.

Calculation of the fiber core power percent by the following equation [24]:

$$\eta = \frac{\int_i S_z dA}{\int_{all} S_z dA} \tag{5}$$

Here, η represents the fiber core power fraction, the area of the core, cladding, or air hole can be computed using the intermigration of the numerator and denominator, where S_z denotes the pointing vector.

The following equation is used to find the V- parameters of H-PCF [25]:

$$V = \frac{2\pi rf}{c}\sqrt{n_{eff}^2 - n_{cl}^2} \le 2.045 \tag{6}$$

where, n_{eff} represents the effective refractive index (RI) which is found form the COMSOL Multiphysics software with the frequency ranges from 0.08 to 3 terahertz (THz) and $n_{cl} = 1.509$, indicates the refractive index of the cladding that is V = 2.93216 × sqrt(neff × neff - ncl × ncl) and r indicates the fiber core radius.

4 Outcomes analysis and deliberations

H-PCF was created using COMSOL Multiphysics simulation software with a frequency range of 0.80–3.0 THz according to Fig. 2. The mode field distributions of X-polarization at 1 THz, whereas waveguide Y-polarization at 1 THz is indicated by Fig. 2a and b, respectively of H-PCF fiber. Our suggested structure features ultra-low effective material loss (EML), decreased scattering loss and confinement loss, all of which are highly beneficial for communications since the total power is tightly constrained to the core region.

Figure 3 depicts the variation of effective area with the increase of frequency in THz region at 62%, 72% and 82% porosity level. It is clear from the characteristics curve that the effective area of H-PCF almost exponentially declines with the rise in frequency at THz region. At 1.0 THz it is found that the value of effective area is around 3.65×10^{-4} m^2, 3.70×10^{-4} m^2 and 4.55×10^{-4} m^2 for 82%, 72% and 62% correspondingly. Here, the ideal parameters are cladding diameter $d_1 = d_2 = d_3 = d_4 = d_5 = 284$ µm, cladding pitch $\Lambda_1 = \Lambda_2 = \Lambda_3 = \Lambda_4 = \Lambda_5 = 375$ µm, core diameter $d_a = 62$ µm, $d_b = 192$ µm, and core pitch $\Lambda_c = 100$ µm.

In the Fig. 4, the characteristics of effective area contrasted with core diameter is shown for three porosity

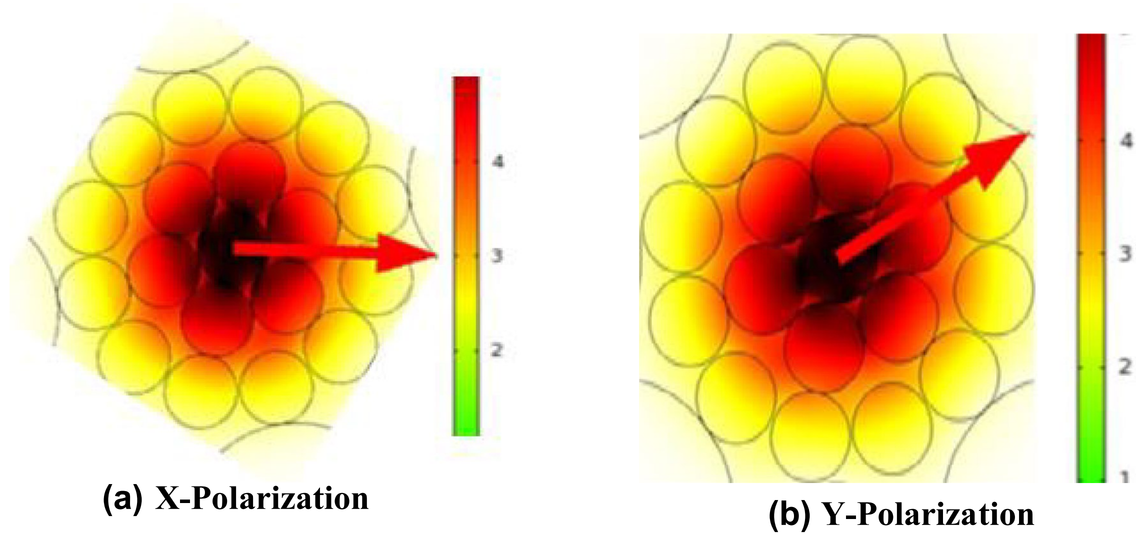

Fig. 2 Electric Mode field distributions for (**a**) x-polarization and (**b**) y-polarization at the controlling region of 1 THz

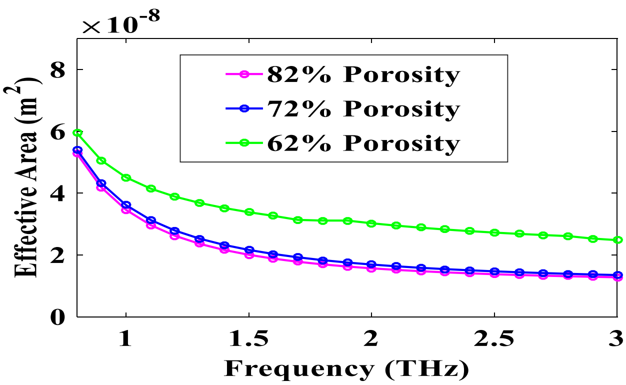

Fig. 3 Effective Area of H-PCF versus Frequency at 82%, 72% and 62% porosity levels

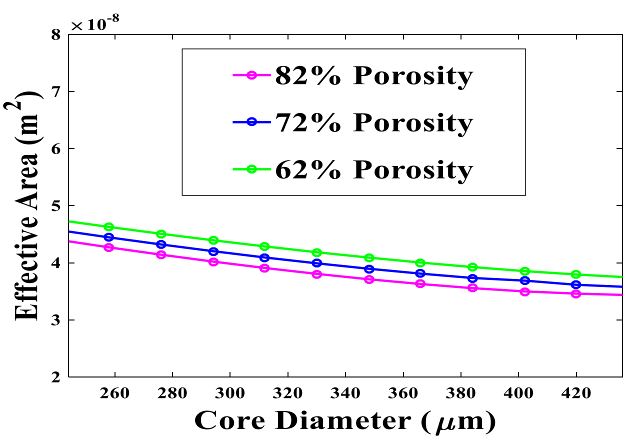

Fig. 4 Effective Area versus of core diameter of H-PCF at 82%, 72% and 62% porosity levels

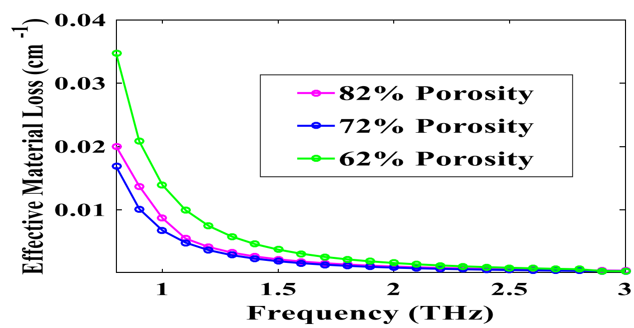

Fig. 5 Effective Material Loss versus frequency (THz) curve at 62%, 72% and 82% porosity levels

level such as 82%, 72% and 62%. As we seen from the characteristics curve it is found that core diameter region (approximately 240 μm to 360 μm) the effective area is not changing the effective area began to grow as core diameter increased to decline at a level up to 440 μm approximately and it shows constant characteristics. At core diameter $D_{core} = 420$ μm, the effective areas are approximately found 4.72×10^{-8}, 4.55×10^{-8} and 4.38×10^{-8} m^2 for 62%, 72% and 82% porosities respectively at 1terahartz (THz) operating frequency.

In the following Fig. 5, depicts the behavior graph of accordance with the fluctuation in effective material loss with the change in frequency in terahertz region for three different porosity levels such as 82%, 72% and 62%. After the simulation procedure form the COMSOL Multiphysics software, we have found that the total amount of lights (data values) transmits within the core area. As a result, this structure shows better graphical results of low effective material loss with the frequency ranges from 0.08 to

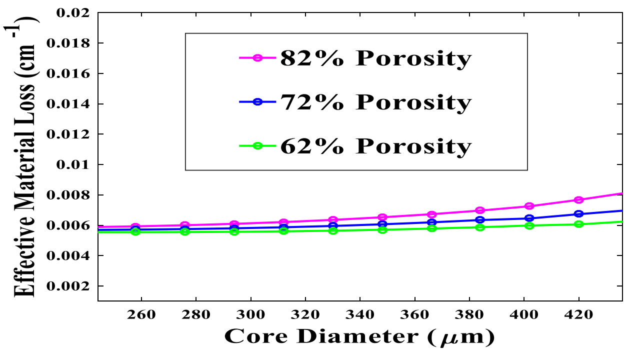

Fig. 6 Relative Sensitivity of EML with the variation of core diameter (micro-meter) for various porosity level

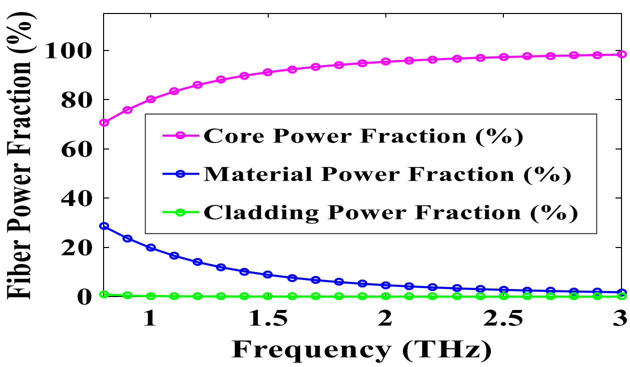

Fig. 7 Power Fraction variation for core, cladding and material versus frequency at THz region

3 terahertz (THz) for 82%, 72% and 62% porosity. Moreover, the attributes graph also shows that is found the EML deteriorations with the rise in frequency at THz region for better communications applications at the three-porosity levels of 82%, 72% and 62%. At 1 THz frequency, the EML are 0.00689 cm^{-1}, 0.00699 cm^{-1} and 0.0149 cm^{-1} for 82%, 72% and 62% porosity correspondingly.

Figure 6 shows the characteristics curve of the effective material loss versus core diameters at micrometer range of the designed H-PCF for the three different porosity levels of 82%, 72% and 62%. It may be shown from the typical graph that with the increase of core diameter the effective material losses decreases for all the defined three different porosity levels. In our proposed H-PCF D_{core} = 420 μm, the EML is about 0.00689 cm^{-1} for 82% core porosity fabricating it in a way that maximizes value while minimizing complexity.

As illustrated in Fig. 7, the power fractions of the core, cladding, and material vary with frequency in the terahertz range. According to the figure, at the cladding area, the power percentage is nearly flat as the frequency increases. In the core region, the power fraction increases with frequency, but after a certain frequency, it remains constant.

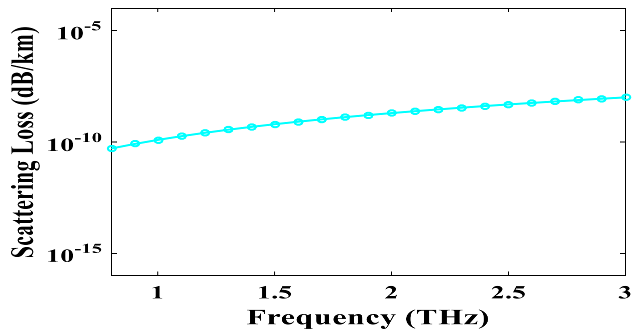

Fig. 8 Scattering loss (dB/km) versus frequency (THz) at optimum design parameters

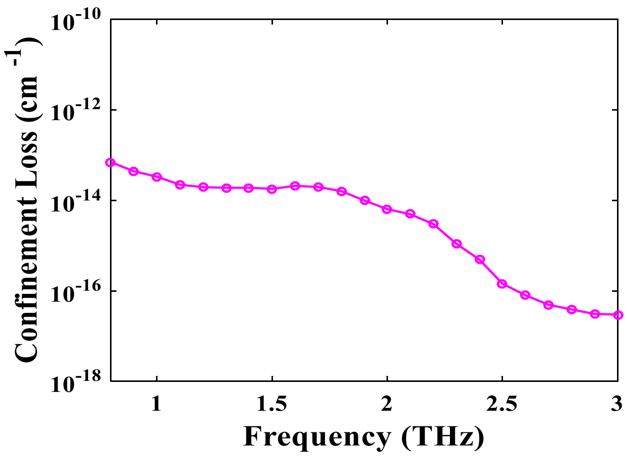

Fig. 9 Variation of Confinement Loss with respect to frequency at THz region at optimum parameters

For material power fraction, As frequency rises, the power fraction declines in terahertz region but after a certain value of frequency the power fraction shows a flat characteristic considering the continued rise in frequency. For 1 THz frequency the power fractions are 0.25%, 20%, 82% for cladding, material and core respectively.

Figure 8 shows a graph of qualities of scattering loss varies with frequency in terahertz region at optimum parameters. It is seen from the characteristics graph that scattering region in dB/km increases with the increase of the frequency in THz. It is also shown that the slope of increasing curve is low that means the scattering loss increasing but slowly with the increase in frequency. This indicates the fact that light was significantly reflected from the core. This H-PCF has achieved a minimal scattering loss of 1.24×10^{-10} dB/km at 1 THz.

Figure 9 shows the variation of Confinement Loss with the increase of the frequency at terahertz region at optimum constraints of the designed H-PCF. Form the graph it is examined that at the starting the confinement loss started decreasing but from 1 to 1.7 THz the confinement

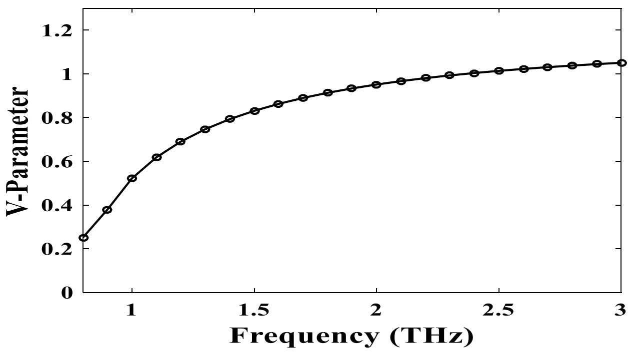

Fig. 10 Features of V-parameter versus frequency at THz for optimum parameters

loss stayed constant and then again decreased but this time the decrease found more gradual than from the starting point. The value of Confinement Loss is found 3.46×10^{-14} cm^{-1} for 1 terahertz in frequency.

The variation of V-parameter with respect to the increase of frequency in the THz range for the intended H-PCF under the ideal design conditions (Single mode fiber) is shown on Fig. 10. From the graph, it is examined that the V-parameter is increasing in proportional to the increase of the frequency at terahertz region up to around 2.10 THz. After 2.10 THz the V-parameter increases a little slowly than before and at after around 3 THz the V-parameters remains constant with the increase in frequency. Due to this, the H-PCF may be used for optical fiber communications applications.

The effective area, EML, confinement loss, scattering loss, Power Fraction, V-parameter characteristics shows a better result by our designed H-PCF at the terahertz region than the previously designed PCF. The comparison results of different parameters that are proposed previously and our proposed H-PCF results are shown in the following Table 1.

We examined different results values of different features from the research of previously suggested PCF and out designed H-PCF in the above comparison table. We discovered that our H-PCF, as intended, produces outstanding results. The comparison table shows that we get the lowest effective material loss (EML) per centimeter from our designed H-PCF, the highest core porosity of 82 percent, a higher core power fraction than previously found core power percentage, larger effective area and less confinement loss from our designed H-PCF. Because our developed H-PCF achieves excellent results in all characteristics areas, it may be used in a variety of important applications, such as broad band transmission. Fabrication method is a significant consideration in the design of H-PCF. PCF may be made in a variety of ways, including jacketing, stacking, collapsing, stretching, and sketching on a traditional drawing tower. However, in recent years, a manufacturing process known as the sol–gel method has become popular for fabricating PCF [35, 38, 39]. As a result, sol–gel will be used as the method to produce our proposed H-PCF in order to obtain a higher-quality PCF fiber.

5 Conclusion

PCF with an elliptical core is designed to achieve ultra-low effective material loss in the THz frequency range. From the hexagonal photonic crystal fiber (H-PCF) design, remarkable outcomes are obtained. At the 1 terahertz waveguide region, the hexagonal photonic crystal fiber (H-PCF) achieves a superior core power fraction of 82 percent, a lower confinement loss of 3.46×10^{-14} cm^{-1}, smallest effective material loss of 0.00689 cm^{-1} and a better effective area of 3.65×10^{-4} m^2. Therefore, we believe that the hexagonal photonic crystal fiber (H-PCF) will be more appropriate and pleasant for optical fiber communication system in the terahertz (THz) range.

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Data availability Data sharing is not applicable to this article.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval No unethical work has been performed in this research work.

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