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Simulation and analysis of ultra-low material loss of single-mode photonic crystal fiber in terahertz (THz) spectrum for communication applications

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Abstract: This analysis represents a circular shape based cladding with two elliptical shape cores in photonic crystal fiber (PCF) for the terahertz (THz) range. Here, we present a single-mode photonic crystal fiber (SM-PCF) with five layers of circular shape of air holes (CAH) structure along with two layers of elliptical shape of air holes (EAH) core configuration in the center to decrease the different types of losses. For broad-band communications, our proposed SM-PCF is highly useful due to the obtaining of ultra-low effective material loss (UML) in the terahertz regime. Perfectly matched layers (PMLs) and finite element method (FEM) established on COMSOL Multiphysics software has been used to design this PCF fiber. Simulated outcomes show a particularly an UML deficit of 0.014 cm^{-1}, power fraction in the core area (CA) and large effective area (EA) of 72%, and 5.90×10^{-8} m^2 respectively at 1 terahertz (THz) frequency. Also, other aspects of optical fiber for THz signal banquet with confinement loss (CL), scattering loss (SL) and V-parameter have been calculated here. Moreover, our proposed SM-PCF shows single-mode propagation by V-parameter pointer over 0.80–3 THz frequency. So, we can say that our designed PCF fiber will be suitable for various effective communication areas at the terahertz (THz) spectrum.

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Keywords: confinement loss; effective material loss; photonic crystal fiber; single mode optical fiber; THz waveguide; V-parameter.

1 Introduction

Recently, researchers have been pointing their attention to the terahertz (THz) area between 0.1 and 10 THz waveguide arrays [1]. There has been embryonic thoughtfulness in low deficit and diffusion trampled waveguide varying free space for expenditures in the THz frequency. This THz waveguide has been succeeded in applications in various areas such as discreet imaging [2], astronomy [3], drug censoring [4], spectroscopy [5], DNA hybridization [6] etc. terahertz (THz) wave propagation is accomplished by controlling light into the air holes since dry air does not fascinate terahertz (THz) waves. To speed up its uses, specialists are engaged to design a consistent and reliable terahertz (THz) waveguide and previously some waveguides were stated by numerous specialists, for instance, numerous metal and dielectric waveguides [7]. Although there are many practical limitations, the viable application of terahertz (THz) microstructure is quiet in the developing stage. These disadvantages comprise the dense terahertz (THz) sources and huge environmental costs in the terahertz (THz) band [8].

Currently, it has been shown by studies that photonic crystal fiber (PCF) hollow-core and polymer porous constructions can be unhurried as effective preferences for terahertz (THz) communication due to its better waveguide features [9, 10]. So recently, to diminish the restrictions, numerous guided media for terahertz (THz) communication have been premeditated and intended [11, 12]. In the PCF, light is focused both on refractive index modifications and physical alterations. Although, PCFs confront extreme material forfeiture if just dense material [13] is smeared in the midpoint. Therefore, a porous air-core (AC) is chosen over a dense core. Light is bounded either by the transformed or altered the entire internal reflection (MTIR) by the photonic bandgap (PBG) force in a PCF region [14]. The upper the refractive index difference regarding the core area (CA) and cladding area (CdA), the more enhancement of the MTIR.

Few studies have been scrutinized by several researchers in recent times for low forfeit terahertz (THz) waveguides [13–25]. Recently, the researchers designed a circular hybrid fiber and resolute an effective material loss (EML) of 0.035 cm^{-1} with a 45% core power percentage and scattering flatness of 1.33 ± 0.07 ps/THz/cm [14]. It has been found [15] an excessive EML of 0.07 cm^{-1} in an octagonal PCF and overlooked several important structural factors such as diffusion and core power fraction. It is suggested by other researchers [16] that revolved hexagonal single-mode porous fiber and long-established an EML of 0.066 cm^{-1} over 40% central power fraction. Though, research in [17] diminished the EML to 0.035 cm^{-1} by presenting a kagome lattice that is nearly difficult to formulate. Thus, it is visible to the condition of own structures that can be expressed readily and this is a considerable field for enlargement of research.

A revolved hexagonal formation in the core through a rounded lattice and attained an EML of 0.053 cm^{-1} with a diffusion deviation of 0.25 ps/THz/cm [18]. To minimize the EML and advance the efficacy of THz communication, researchers designed another waveguide in [19] consenting EML of 0.047 cm^{-1} and diffusion deviation of 0.15 ps/THz/cm. Lately, a double hole unit-based kagome cladded PCF has been premeditated [20] where they attained an EML of 0.052 cm^{-1} with an extreme value of confinement forfeit of 0.01 cm^{-1} and high diffusion flatness of 2.7 ± 0.49 ps/THz/cm. A bandgap fiber with a honeycomb structure was designed by Bao [21] where they found an excessive EML of 0.35 cm^{-1} and prohibitive coupling loss of 5 dB.

Imran Hasan et al. [22] suggested the porous core based octagonal PCF (PC-OPCF) and shows the high EML of 0.056 cm^{-1} and high confinement loss at 1.0 THz. Saiful Islam et al. [23] proposed Zeonex-based PCF displays the low birefringence and the high EML of 0.06 cm^{-1} for optimum design parameters. Jakeya Sultana et al. [24] explained the Zeonex based diamond-shaped core kagome lattice PCF and shows the high EML of 0.04 cm^{-1} with high confinement loss at 1.0 THz. On the other hand, Zeonex based oligoporous-core PCF were designed by Saiful Islam et al. [25] and discloses the low core power fraction, low birefringence and the high EML of 0.05 cm^{-1} at 1.0 THz. After linking formerly reported articles [13–25], it is understood that there is a large scope to design and adapting the PCF construction to attain the finest optical guidance possessions in the THz frequency area.

In this study, ultra-low material loss (UML) of single-mode photonic crystal fiber (SM-PCF) for Terahertz (THz) spectrum containing standard circular shape five-layer circular air holes (CAH) in the cladding region with two elliptical air holes formed in the core has been proposed and designed for effective transmission of terahertz (THz) waveguide. On the other hand, Zeonex (Cyclo-olefin polymer) [26] with refractive index (n = 1.52) is seen to be strongly used to reducing the different types of loss for communication applications for dielectric material characterization such as absorption coefficients, dielectric loss tangents, transparency, and thermal and chemical stabilities. So, we have used the Zeonex (Cyclo-olefin polymer) as a background material and the obtainable structure is sensibly effective in terms of an ultra-low EML of 0.014 cm^{-1}, a large effective area of 5.90×10^{-8} m^2, and power fraction in the core area of 72% at 1 terahertz (THz) frequency range than current design [27–34]. As EML is the leading anxiety of the intended waveguide, it is furthermore authoritative to improve the other guiding features including confinement loss (CL), scattering loss (SL), V-parameter and single-mode propagation.

2 Design methodology

The geometry views of SM-PCF disclose the two elliptical based air holes in the core region, five layers based on CAH in the cladding region, and mode field distribution in Figure 1. 8, 16, 32, 64 and 128 respectively are the air holes of the number of first, second, third, fourth and fifth layer at the cladding region. The distance of hole to hole within two or the same air holes is defined by the pitch. In the cladding region, the parameters Λ_1 and d_1 are indicated by the pitch and diameter of the air holes.

In the core region, the pitch and diameters of the two elliptical air holes are denoted with the parameters of Λ_c, d_a, and d_b. In this SM-PCF structure, the background material of Zeonex *i*th refractive index (n = 1.52) is used to reduce the confinement loss, the scattering loss, and the EML. We have used two elliptical holes because to reduce the EML and to avoid fabrication complexity strongly. As a result, we hope that our proposed fiber (C-PCF) will be strongly suitable in different communication areas in the terahertz (THz) waveguide with the strongly graphical results with removing the EML than the previous articles. In the cladding area, the air filling ratio is defined by the parameters of d_1/Λ_1 and this ratio helps to avoid the fabrication complexity between the two air holes. Here, the thickness of PML (boundary condition) is determined by the 10% of the maximum fiber diameter. Moreover, the optimum parameters are cladding diameter d_1 = 260 m,

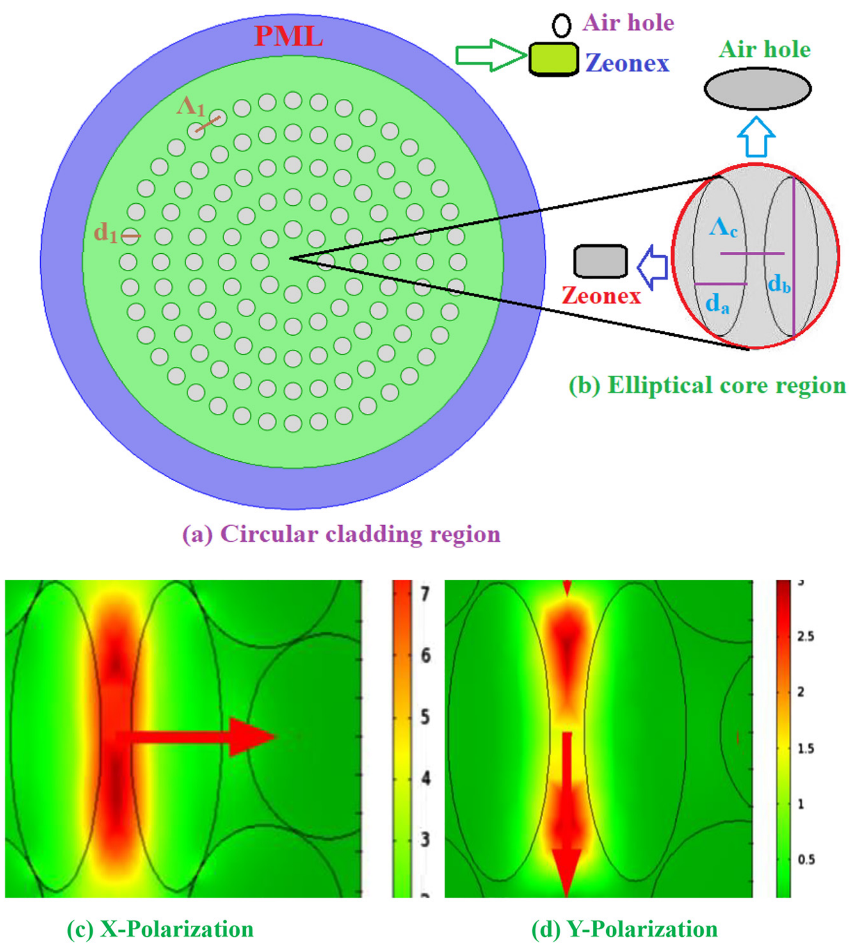

Figure 1: The geometry views of single-mode photonic crystal fiber (SM-PCF) fiber with (a) circular cladding region, (b) elliptical core region, (c) X-Polarization and (d) Y-Polarization.

cladding diameter $d_2 = d_3 = d_4 = d_5 = 290$ m, cladding pitch $\Lambda_1 = 345$ m, cladding pitch $\Lambda_2 = \Lambda_3 = \Lambda_4 = \Lambda_5 = \Lambda_6 = 340$ m, core diameter $d_a = 70$ m, $d_b = 190$ m and core pitch $\Lambda_c = 90$ m. So, we can say strongly that the finite element method (FEM) method with the PML layers based COMSOL Multiphysics software is used to design this SM-PCF structure to obtain the better optical features like as V-parameter, CL, scattering loss, effective area, power fraction, and the ultra-low effective material loss (U-EML) according to the terahertz frequency wave ranges from 0.80 to 3 THz.

3 Numerical analysis

All-optical characteristics are computed by the method of FEM with the perfectly matched layers (PML) boundary circumstance based COMSOL Multiphysics software tool. We know that an effective area is a significant optical characteristic of the optical-based PCF fiber. Moreover, a larger effective area-based PCF structure displays the UML. As a result, this larger effective area-based PCF fiber is highly appropriate for long-distance communication applications. Here, the effective area is determined by [35, 36]:

$$A_{\text{eff}} = \frac{\left[\int I(r) r \mathrm{d}r\right]^2}{\left[\int I^2(r) \mathrm{d}r\right]^2} \tag{1}$$

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

Another essential optical property of the power fraction is defined with the total amount of power flowing into the PCF fiber. Here, power fraction is calculated through the following way [27, 37]:

$$\eta = \frac{\int_i S_z \mathrm{d}A}{\int_{\text{all}} S_z \mathrm{d}A} \tag{2}$$

where cladding, core, or air hole is denoted by the area of interest with the nominator integration and the entire cross-section area is indicated by the denominator integration.

V-parameter defines the mode propagation of the PCF optical fiber. Here, V-parameter is computed by [28]:

$$V = \frac{2\pi rf}{c}\sqrt{n_{co}^2 - n_{cl}^2} \leq 2.045 \quad (3)$$

where n_{co} and n_{cl} is defined by the core and cladding area based of effective refractive index and the radius of the core is r.

Low confinement based PCF fiber performs better in the communication areas. Here, confinement loss L_c is calculated by [29]:

$$L_c = 8.686 \times K_0 \quad \text{Im}\left[\, n_{eff} \,\right] \quad (\text{dB/m}) \quad (4)$$

where $K_0 = (f/c)$ is the free wave number with the speed of photon c and f is frequency, Im $[n_{eff}]$ is defined by the imaginary part of effective refractive index (RI).

The total amount of loss is determined by the SL of the PCF structure. Here, the SL is computed by [30]:

$$\alpha_R = C_R \times \left(\frac{f}{c}\right)^4 (\text{dB/km}) \quad (5)$$

where the scattering coefficient is mentioned by C_R.

In this SM-PCF fiber, the background material is used as a Zeonex and helps to minimize strongly the EML with the high-frequency range of wave pulse. So, EML is calculated by [31]:

$$\alpha_{eff} = \sqrt{\frac{\varepsilon_0}{\mu_0}}\left(\frac{\int_{mat} n_{mat|E|^{2}\alpha_{mat}}\, dA}{\left|\int_{all} S_z dA\right|}\right)(\text{cm}^{-1}) \quad (6)$$

where the relative permittivity and the permeability of free space are denoted by ε_0 and μ_0, the RI of the material is n_{mat} and bulk material absorption loss is α_{mat}. Pointing vector $S_z = ½\,(E \times H^*)$. The electric field components is E and H^* is the complex parameters of the magnetic field.

4 Numerical results analysis and discussions

In this SM-PCF fiber, we get all graphical results with the PML layers and the FEM method based COMSOL Multiphysics software. In the figure from 2 to 9, it is clearly seen that the total amount of lights or power are tightly confined in the core area. As a result, we find the better graphical results of optical properties such as scattering loss, the low EML, effective area, power fraction, V-parameter, confinement loss with the frequency ranges from 0.80 to 3 THz.

Figure 2 presents the EA of the designed PCF for frequency difference along with functional porosity differences for instance 62, 72, and 82%. For high bit frequency communications, the large modal region is significant. The effective region of a PCF describes the capability to

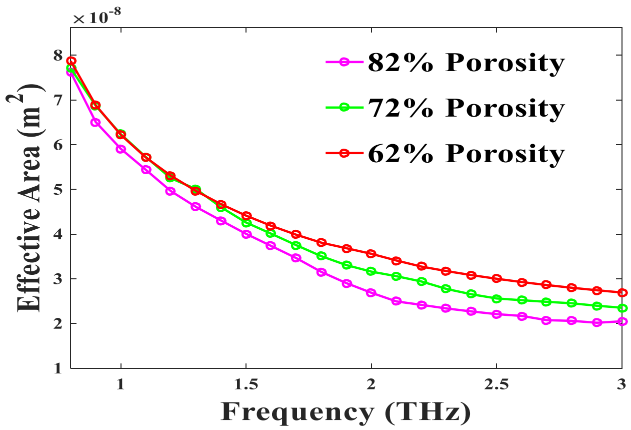

Figure 2: Effective area region of designed SM-PCF fiber at various frequencies for 82, 72 and 62% porosities.

handover data in a diffusion medium. From Figure 2, escalation in frequency decreases the effective region is shown. At minimal frequency, the mode power creates closely within the core extent, thus the guiding waves disperse extensively. It is also understood that all occurrences of functional porosity; the effective region remains level after 2.5 THz functional frequency. The effective region is projected as 5.90×10^{-8} m^2, 6.23×10^{-8} m^2, and 6.21×10^{-8} m^2 for 82, 72, and 62% porosities respectively at 1 THz frequency.

The impact of core distance for various porosities as 62, 72, and 82% on the effective area of designed PCF has been described in Figure 3. Effective area decays with the escalation of core expanse. It also reflects that the effective area becomes closely level after $D_{core} = 292$ µm to $D_{core} = 392$ µm. For optimum core diameter $D_{core} = 372$ µm, the effective area is expected as 5.15×10^{-8} m^2, 6.25×10^{-8} m^2, and 6.22×10^{-8} m^2 for 82, 72, and 62% porosities respectively for 1 THz frequency.

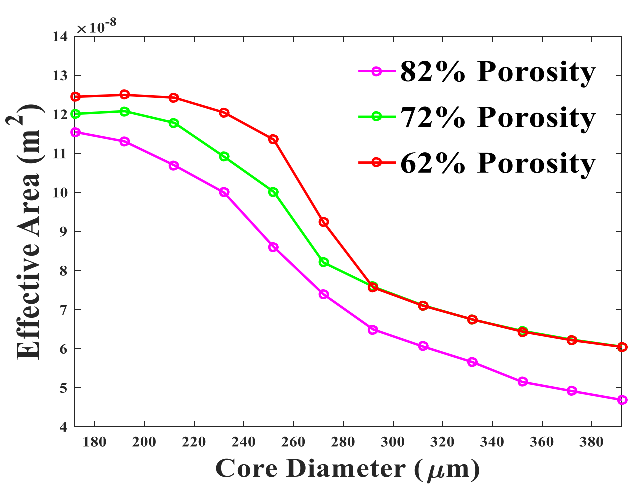

Figure 3: Effective area region of designed SM-PCF fiber at various core diameters for 82, 72 and 62% porosities with 1 THz frequency.

The EML of the proposed PCF has been shown by frequency adjustment in Figure 4 and it has been accomplished that EML debilities with the escalating of frequency. For ideal conditions at 1 THz frequency, the EMLs continue 0.017 cm^{-1}, 0.023 cm^{-1} and 0.014 cm^{-1} for 62, 72 and 82% porosities respectively.

Figure 5 highlights the influence of various core diameters and EML for the x-polarization procedure which can be made-up for vital core diameter D_{core} magnitudes the constraint of EML debilities with the extents of D_{core}. The substantial explanation belated this feature is that the measurements of material within the core declines as the porosity increases that eventually decays the amount of EML. The EML frequently intensifies marginally with positive porosity standards as the core diameter rises for both polarizations. Therefore, for D_{core} = 372 m, porosity = 82% frequency f = 1 THz, and the EML is around 0.014 cm^{-1} at optimum design concerns.

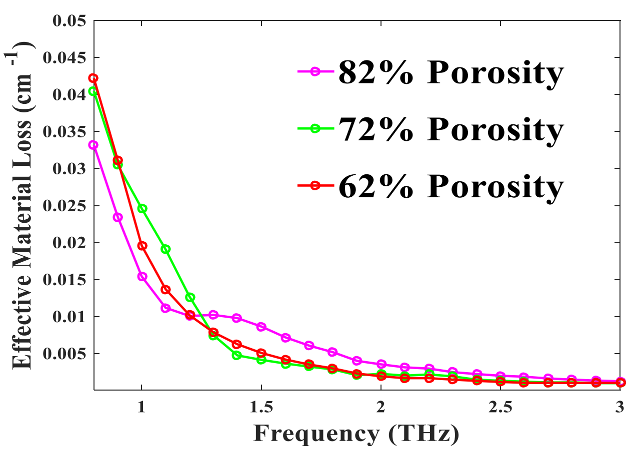

Figure 4: Effective material loss (EML) versus frequency for 62, 72 and 82% porosities.

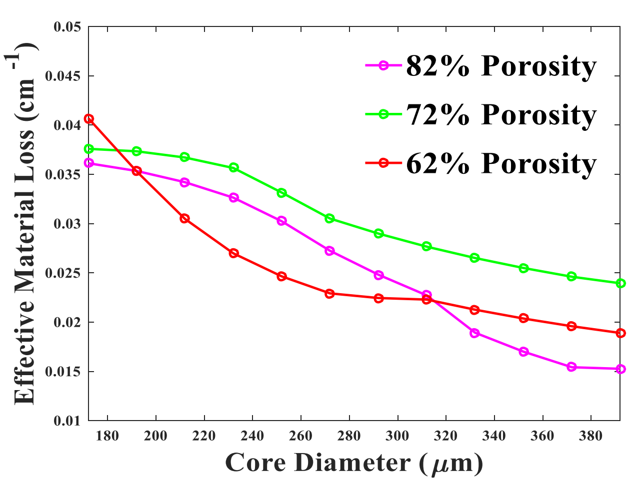

Figure 5: EML versus core diameters for 82, 72 and 62% porosities with 1 THz frequency.

Power fraction procedures the volume in (%) of optical energy that tides through the fiber, in practice, the core, cladding, and material. When the power fraction value is high it concludes that the optical capability is beyond effective of deportment. Optical power communiqué through numerous units of fiber is not abstemiously identical and accordingly, the power fraction is confirmed individually. The curve of core, cladding, and material power fraction through the frequency arrangement from 0.80 to 3 THz is shown in Figure 6. It is markedly supposed that the highest volume of power enterprises in the core area of PCF that directs the maximum volume of light association with analytes at this opinion. The power fractions of core, cladding, and materials are 72, 2, and 26% respectively with frequency 1 THz.

Scattering loss with differences of functional frequency is studied for the designed structure in Figure 7 where it grants that the light attentively permits throughout the core area and consequences in marginal scattering loss.

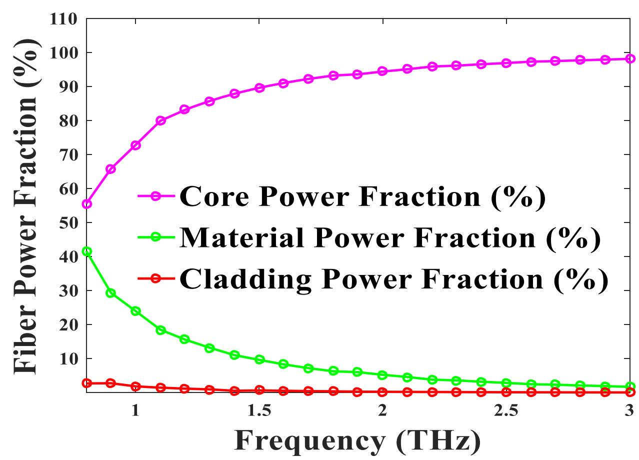

Figure 6: Power fraction versus of various frequencies for optimal design considerations.

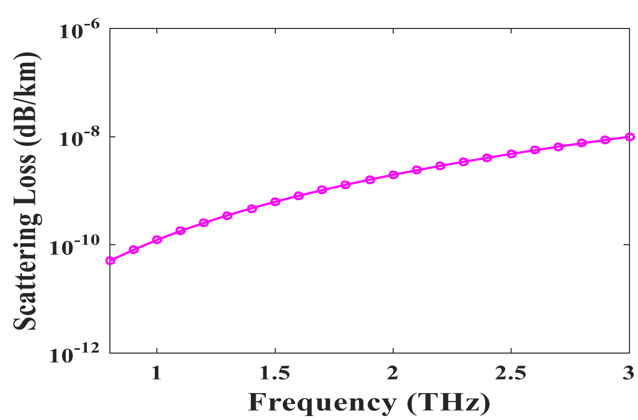

Figure 7: Scattering loss of the designed SM-PCF is estimated at various frequencies for optimum outline parameters.

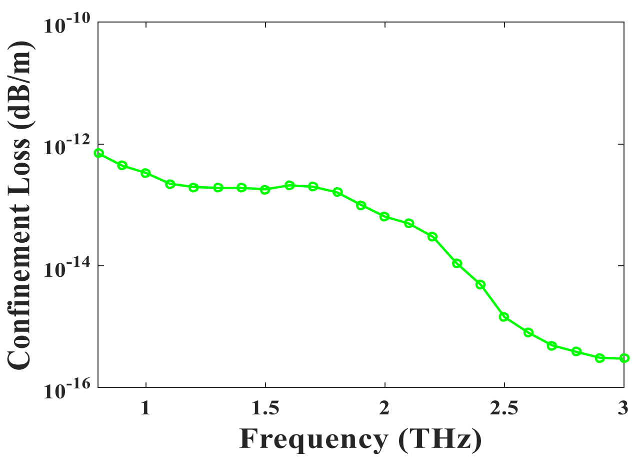

Figure 8: Confinement loss of proposed SM-PCF fiber at different frequencies for optimum design parameters.

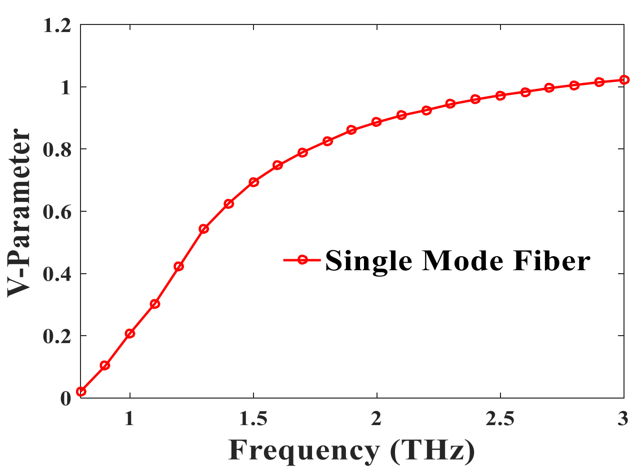

Figure 9: V-parameter of the designed SM-PCF is computed at various frequencies for optimum design.

The scattering loss is comprised since it delivers a complete forfeit of a fiber. Figure 7 furthermore explains that the scattering loss decays as the changing of optical varieties. The scattering loss accomplished for 82% porosity of this layout is 1.23×10^{-10} dB/km at 1 THz frequency. The loss of scattering is falling in measures thus the total loss is not severely pretentious.

Figure 8 illuminates the CL of the proposed fiber supposed for the numerous functional frequencies. Here, confinement losses are perceived to decay by the rising of frequency at the uniform value of D_{core}. Escalating of frequencies yields a substantial difference between CA and C_dA. Light is occupied nearly in the core area and therefore declines the loss of containment. It is considered that the confinement loss for the designed structures at optimum thoughts for 1 THz of the order of 3.34×10^{-13} dB/m.

The V-parameter as a portion of the functional frequency range (0.80 THz to 3 THz) has looked in Figure 9 and it can be pragmatic from this figure that V-parameter extends slightly with the swelling of frequency. Moreover, it is supposed that the degree of the V-parameter through the total functional frequency range remnants beneath 2.405. Thus, the proposed SM-PCF turns in a distinctive mode complaint which accomplishes as the wide area of communication applications. Once settling all measured results from Figure 6 to Figure 9, it is comprehended that each graphical outcome is fabricated by the optimal elements for the THz frequency range. Now, the proposed design of optimum elements is cladding diameter d_1 = 260 μm, cladding diameter $d_2 = d_3 = d_4 = d_5$ = 290 μm, cladding pitch Λ_1 = 345 μm, cladding pitch $\Lambda_2 = \Lambda_3 = \Lambda_4 = \Lambda_5 = \Lambda_6$ = 340 μm, core diameter d_a = 70 μm, d_b = 190 μm and core pitch Λ_c = 90 μm.

Table 1: Comparison of guiding features of the proposed SM-PCF and previously designed waveguides.

Ref.	EML (cm^{-1})	Porosity (%)	Power fraction (%)	Confinement loss (dB/m)	Effective area (A_{eff} (m^2))
[32]	0.100	30	–	1.0×10^{-01}	2.3×10^{-07}
[33]	0.089	60	37%	1.0×10^{-02}	9.77×10^{-08}
[34]	0.076	80	53%	8.96×10^{-01}	–
[38]	0.038	74	56%	2.35×10^{-01}	6.75×10^{-05}
[39]	0.110	–	–	–	0.98×10^{-07}
[40]	0.027	85	83%	1.0×10^{-02}	9.48×10^{-08}
[41]	0.068	50	–	–	–
[42]	0.050	60	42%	1.00	–
[43]	0.07	30	–	1.14×10^{-3}	1.07×10^{-9}
[44]	0.05	–	67%	7.79×10^{-12}	2.00×10^{-5}
[45]	0.078	30	–	1.39×10^{-4}	–
[46]	0.043	81	47%	1.00×10^{-2}	2.15×10^{-5}
Proposed SM-PCF	0.014	82	72%	3.34×10^{-13}	5.90×10^{-8}

The designed SM-PCF specifies outstanding EML, Confinement forfeit, Core power fraction, and effective region possessions than other designed PCFs at 1 THz functional frequency as provided in Table 1.

It is observed from the above analysis and valuation possessions of Table 1 that the proposed PCF design will play a significant role in numerous wideband transmission applications in THz microtechnology.

5 Fabrication possibilities

The fabrication procedure is a crucial matter in any design. There are many fabrication procedures is useful practically to fabricate the PCF for instance stack and draw, tube stacking drilling and sol–gel [47, 48]. However, the sol–gel [49, 50] method contributions to design the PCF formation simply and easy to implementation. So, we can say that the sol–gel method will be more suitable to fabricate our designed PCF fiber.

6 Conclusion

In this article, our proposed PCF is designed for in the THz frequency regime to obtain low EML, low confinement loss and scattering loss for numerous communication applications. The suggested fiber of SM-PCF contains five layers CAH in the cladding region and two elliptical in the core area that have been presented in this research work. All graphical results have been obtained by PML and FEM methods with the terahertz (THz) frequency ranges from 0.80 to 3 THz. In this two elliptical core-based SM-PCF, the simulation results show a U-EML, large effective area and core power fraction of 0.014 cm^{-1}, 5.90×10^{-8} m^2 and 72% respectively at 1 THz frequency range. Moreover, a low confinement loss and scattering loss such as 3.34×10^{-13} dB/m and 1.23×10^{-10} dB/km has been achieved from the proposed PCF at 1 THz frequency area. So, it is strongly seen that the PCF structure can be useful in various THz communication applications.

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Availability of data and material: This paper has sufficient data which has been taken from COMSOL Multiphysics software by simulation the work.
Compliance with ethical standards: The plagiarism of this paper is enough to publish the work. It is not more than 20% which is good enough internationally.
Consent to participate: All of the authors are agreed to submit this paper here. The authors declare that they have no conflict of interest.
Consent for Publication: We are agreed to publish the work if accept in this journal.

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