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Research article

Design of Low Loss Porous Core Fiber for Terahertz Regime using Zeonex

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A B S T R A C T

In this research, a Zeonex-based single-mode micro-structured fiber with a hybrid cladding is proposed for THz wave propagation. The investigation utilizes the Finite Element Method (FEM) with a Perfectly Matched Layer (PML) boundary condition to examine key parameters such as single-modeness, effective mode area, confinement loss, and dispersion. Simulation results indicate a very low effective loss due to absorption at an operating frequency of 1 THz (0.04 cm−1). A flat dispersion (0.73 ± 0.13 ps/THz/cm) is also observed over a large bandwidth (0.5–1.4 THz). Zeonex, a cyclo-olefin polymer (COP), is selected as the base material due to its favorable properties, including its suitability for fiber drawing. The proposed fiber can be fabricated using existing fabrication techniques and is suitable for THz band applications.

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1. INTRODUCTION

In recent years, Terahertz (THz) waves, typically identified as covering the 0.1- to 10-THz frequency band, have garnered significant attention. Numerous applications of this radiation have been reported, including medical diagnostics defect detection in electronic circuits and pharmaceutical drug testing among others [1-4]. In the THz regime, devices can be employed in hazardous or security-sensitive areas for monitoring drugs gases explosives and weapons. Additionally, THz waves have been valuable for studying the kinetics of complex natural biological systems. This growing interest has spurred the development of improved THz sources and detectors, leading to significant technical advancements in THz wave generation and detection [5-11] .

Most commercially available THz systems rely on free-space transmission due to the lack of suitable low-loss flexible waveguides. Previously,

circular metallic guides such as stainless steel wires and hypodermic needles were considered, but these waveguides exhibit high loss [12, 13]. A THz wave cannot be efficiently guided inside a hollow dielectric tube. However, a plasmonic mode can form within the hollow core if the dielectric tube is coated with a metallic layer, allowing for better control and manipulation of the guiding environment [14].

The development of optical fibers (OFs) in 1966 revolutionized fields such as telecommunications, sensing technology, and control systems based on light guidance. Optical fibers offer remarkable advantages, including geometrical versatility, increased sensitivity of existing techniques, and essential compatibility with fiber optic telecommunications technology. This makes them ideal for sensing applications in various industries. Optical fiber-based sensors provide cost-effective and efficient solutions due to their small size, high sensitivity, flexibility, robustness, and capability for remote monitoring and multiplexing. They are suitable for use even in harsh environmental conditions, such as high voltages, electromagnetic interference, chemically corrosive media, nuclear radiation, and extreme temperatures.

A key limitation in the advancement of optical fiber technology has been the intrinsic properties of silica. However, the introduction of photonic crystal fibers (PCFs) in 1996 was a breakthrough that overcame many limitations of standard optical fibers. Photonic crystal fibers consist of a periodic arrangement of air holes running along the fiber's length, with a porous core at the center. The properties of these fibers depend not on spatially varying glass compositions, as in conventional fibers, but on the arrangement of these air holes. Unlike standard fibers, PCFs can be manufactured as a single element, with their geometric parameters offering substantial design flexibility [15].

Various materials, such as polymethyl methacrylate (PMMA), high-density polyethylene (HDPE), Teflon and Topas have been used to design THz waveguides. Recent simulations and experiments have frequently used Topas due to its favorable qualities, including lower water absorption, low material absorption loss (0.2 cm−1), and a higher glass transition temperature than PMMA, making it suitable for biosensing. However, a newer cyclo-olefin polymer (COP), Zeonex has been selected for the proposed model as the background material due to its unique advantages over Topas. Zeonex offers lower impurity content, a lower loss tangent, a lower dielectric constant, and greater heat resistance. It also has a low specific gravity, high chemical resistance, superior transparency, and a lower melt flow index at high temperatures. Additionally, Zeonex's physical properties make it more suitable for high-quality fiber drawing compared to Topas, as it provides a wide range of drawing stress, facilitating easier fabrication [16].

2. MATERIALS AND METHODOLOGY FOR THZ FIBER DESIGN AND EVALUATION

The research work was conducted in several stages. Initially, after finalizing the research topic, a thorough study of the fundamental theories related to TOPAS, Teflon, and Zeonex was carried out to support the research. Following this, the benefits of using porous core fibers for Terahertz applications were reviewed. The limitations of existing architectures were analyzed, leading to the development of the proposed speaker recognition architecture. Once the design was finalized, the overall method was implemented. To evaluate the proposed model, a well-known dataset was utilized, and tests and evaluations were conducted on the implemented architecture. Lastly, the thesis writing process was completed. Figure 1 presents a flow diagram outlining the steps of the research procedure.

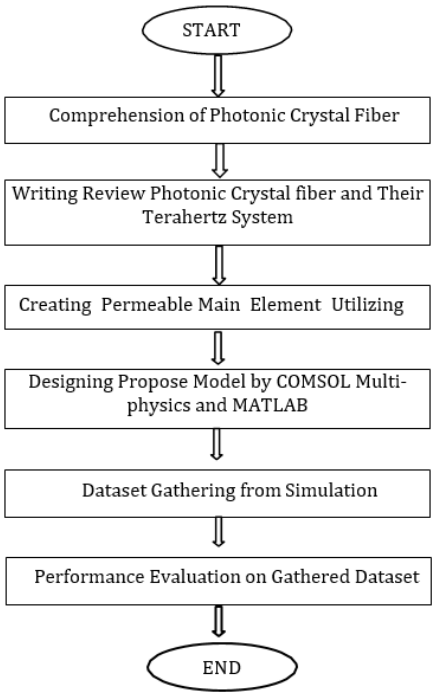


Fig. 1. Flow Diagram of Research Procedure.

2.1 Problem Analysis

In designing a terahertz (THz) waveguide, the primary challenge is minimizing the high material absorption loss of the background material. One effective strategy to reduce this loss is by increasing the core power fraction and ensuring tight confinement between the core's air holes. This approach allows for a better concentration of energy in the core, reducing overall losses. In photonic crystal fiber (PCF) design, beyond considering effective material loss (EML) and confinement loss, it is crucial to focus on the amount of useful power transmitted through the core air holes, which directly impacts the waveguide's performance.

The design objective is to achieve a higher core power fraction, which can be calculated using the following formula:

$$\acute{\eta} = \frac{\int x \; S_Z \, dA}{\int all \; S_Z \, dA} \tag{1}$$

where ή represents mode power fraction and X represents the region covered by air holes. Following, the dispersion property of the proposed fiber must be observed. In this inquire about work, as it where waveguide dispersion has been considered since the refractive list of TOPAS is constant between the frequency ranges of 0.1–1.5 THz, where material dispersion can completely be dismissed. Our plan objective is to get the flattest dispersion conceivable, which can be calculated by

$$\beta_2 = \frac{2}{c} \frac{dn_{eff}}{dw} + \frac{w}{c} \frac{d^2 n_{eff}}{dw^2} \tag{2}$$

At last, we characterize the effective mode area *A*eff of the proposed fiber, which can be calculated by

$$A_{eff} = \frac{[\int I(r) r dr]^2}{[\int I^2(r) \, dr]^2} \tag{3}$$

where $I(r) = |Et|^2$is defined as the transverse electric field intensity distribution in thecross-section of the fiber.

2.2 Design, Implementation and Simulation

The design and simulation of the proposed photonic crystal fiber (PCF) model were conducted using COMSOL 5.3a, a finite element method (FEM)-based software. Figure 2 illustrates the cross-sectional view of the proposed PCF, along with an enlarged version of the core. The elliptical core features a major axis and a minor axis with lengths of 2a and 2b, respectively. To ensure the core's stability within the fiber, horizontally and vertically aligned struts were incorporated. Due to the suspended nature of the core, the refractive index of the cladding region is approximated as unity.

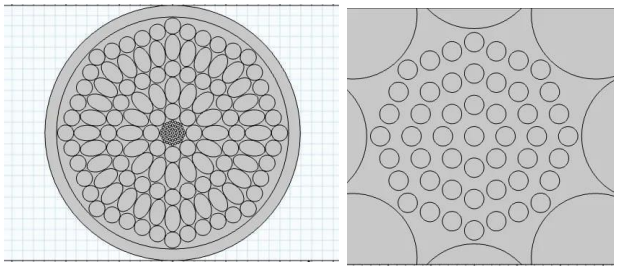


Fig. 2. Cross Section of the Proposed Model.

This design approach enhances modal confinement within the core. The vertically adjusted strut is intentionally larger than the horizontally adjusted strut, introducing asymmetry into the structure. Both struts have a thickness of 0.476a and a length of 12.753a. Within the core, a set of eight additional struts, each with a thickness of 0.019a but varying lengths (L1, L2, L3, L4), is incorporated. The lengths of these struts are set to 0.663a, 0.704a, 0.722a, and 0.737a, respectively. The core pitch, denoted as Λc, represents the distance between two adjacent struts and is established at 0.08a and 0.18a for this design. The dimensions of the core air slots within the core region are determined by the major axis length of 2a. In this model, an optimal porosity of 75% is chosen, resulting in a total fiber diameter of 14.67a. The ideal dimensions for the major and minor axes of the core are set to 2a = 540 μm and 2b = 240 μm, respectively, with a core porosity of 75% and an operating frequency of 1 THz.

Various materials can be utilized for designing terahertz waveguides, including polymethyl methacrylate (PMMA), high-density polyethylene (HDPE), Teflon, and Topas. Recent simulations and experimental works on THz waveguides have predominantly focused on Topas due to its favorable properties, such as lower water absorption, minimal material absorption loss (0.2 cm^{-1}), and a significantly higher glass transition temperature (Tg) compared to PMMA, making it suitable for biosensing applications. Additionally, Topas maintains a consistent refractive index (1.535) across a wide terahertz frequency range, resulting in negligible chromatic dispersion [17].

However, we have selected a recent cyclo-olefin polymer (COP), Zeonex, as the foundational material for both proposed models. Zeonex offers unique advantages over Topas, including a lower impurity content, enhanced thermal resistance, lower dielectric constant, and reduced loss tangent. It also features lower specific gravity, higher chemical resistance at elevated temperatures, greater transparency, and a lower melt flow index. The physical properties of Zeonex are more favorable for producing high-quality fiber compared to Topas, as it reduces fluctuations in fiber diameter due to its improved drawing stability, providing greater design flexibility. Additionally, Zeonex allows for a broader range of drawing stress, facilitating easier fabrication.

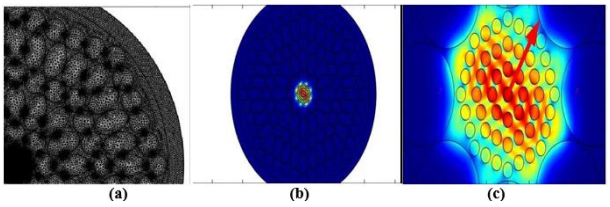


Fig. 3. (a) Mesh of the Proposed PCF Model; Mode field distribution for at Lc = 370µm and f = 1 THz.

Figure 3 illustrates the tight confinement of modal control within the fiber core for the x-polarized mode compared to the y-polarized mode. This phenomenon arises from the vertically aligned openings in the elliptical core, which create asymmetry and induce a higher index contrast between the two orthogonal polarized modes within the core region. Consequently, this configuration allows the modal power of the x-polarized mode to be confined more tightly, resulting in lower control loss for this mode. In contrast, the material absorption loss behaves differently. While we focus on material absorption loss, it is observed to be lower for the y-polarized mode, which exhibits minimal confinement loss. Therefore, the y-polarized mode was considered throughout the entire simulation period.

Some light can be observed in the cladding region due to the modal control flow dispersion depicted in Figure 3. This suggests the presence of additional modes within the fiber, alongside the fundamental mode; however, for these other modes, light will primarily propagate through the fiber cladding region. Consequently, when a pulse of light is introduced at the center of the fiber, only the fundamental mode will propagate through the core region. The guiding mechanism in such photonic crystal fibers (PCFs) relies on modified total internal reflection (MTIR).

3. RESULTS AND DISCUSSION

Effective Refractive Index

Effective refractive index is plotted against different frequency (f) and as seen in Fig. 4.

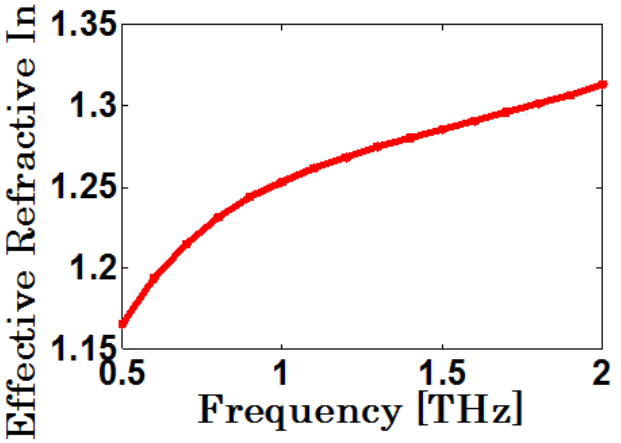


Fig. 4. Effective Refractive Index as a Function of Frequency at D_{core} = 370 µm.

It is observed that effective index increases with the increase in frequency. As the refractive index is a function of frequency, it is also increased with the increase in frequency and decreases after certain frequency. However, increase in material in core causes higher effective material loss. The result is that, the effective refractive index of polarization modes also decreases which Resulting in less value of birefringence. At optimum core length of 370 µm and at operating frequency of 1 THz, the refractive index is 1.222.

EML (Effective Material Loss)

Effective material loss (EML) as a function of core-frequency *(f)* is seen in the Fig. 5. From the figure, we see that EML increases with the increase in f. It is because at higher core length the solid material in the core region is increased, as a result, EML is increased. According to the empirical formula $(v) = v^2 + 0.63v - 0.68$, cm^{-1}, where ν stands for frequency, we can also conclude that, EML is increased with the increase in frequency. It is because of the porous core fiber, which confines more and more of the light into the solid material between the holes as the frequency gets higher.

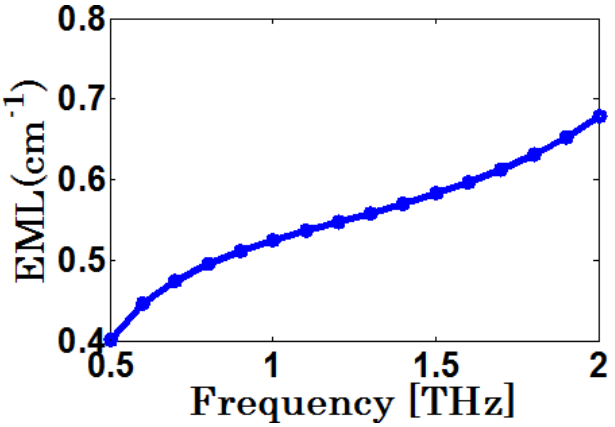


Fig. 5. EML as a Function of Frequency.

Although at smaller core length and lower frequency, EML is much lower we have picked *Dcore* = 370 µm as optimal core length and f =1 THz as optimal operating frequency. Because at *Dcore* = 370 µm and f = 1 THz, the confinement loss is very low and modal power flowing through core air-hole are higher. At optimum core porosity, core diameter, the effective material loss is only 0.09671cm^{-1}. This obtained value is obviously less than that of the works previously reported.

Dispersion

Figure 6, shows the variation of dispersion for both x and y polarization modes as a function of frequency. From the Fig. 6, it is seen that, at optimum core length and core porosity, dispersion is lower and flatter than that of previously reported works and it decreases with frequency. It is about 01.157±0.10ps/THz/cm and remains flat at higher frequencies. Here, we encountered almost gradually decreasing dispersion which is a very good for the fiber transmission.

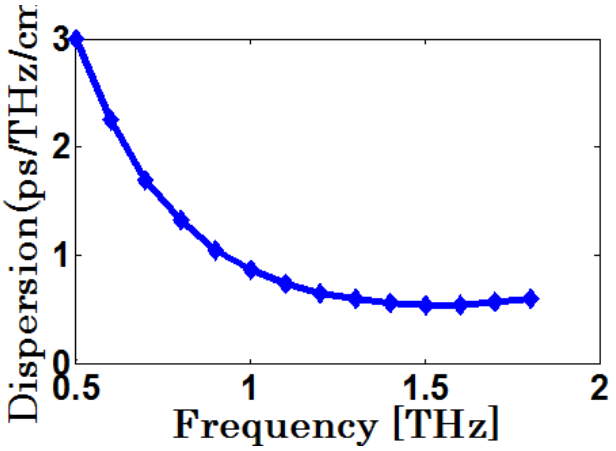


Fig. 6. Dispersion as a Function of Frequency.

Confinement loss

From Fig. 7, able to see thatthe confinement loss reduces with the increment in frequency. It is due to the fact that, at higher core length and frequency, the refractive index distinction between core and cladding increments and consequently the modal power is forced to be propagated through the core. This loss component can too be minimized either by increasing the number of air-holes or porosity of the cladding. At ideal core porosity, working frequency and core diameter, the value of the confinement loss is negligible compared to effective material loss and it is about 3.366×10^{-8}cm^{-1}.

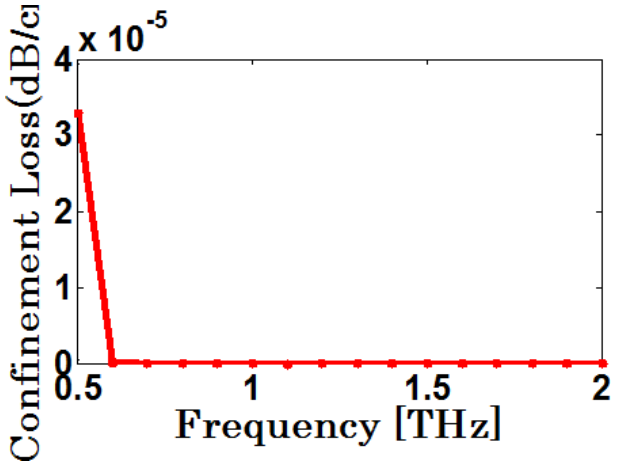


Fig. 7. Confinement Loss as a Function of Frequency.

Core Power Fraction

Figure 8 shows the variation of core power fraction for various frequency (f). It is seen that, at higher frequency, the percentage of the modal power in the core airholes is increased.At optimum core porosity, frequency and core diameter, it is about 41.57%and it is much higher than that of any reported works.

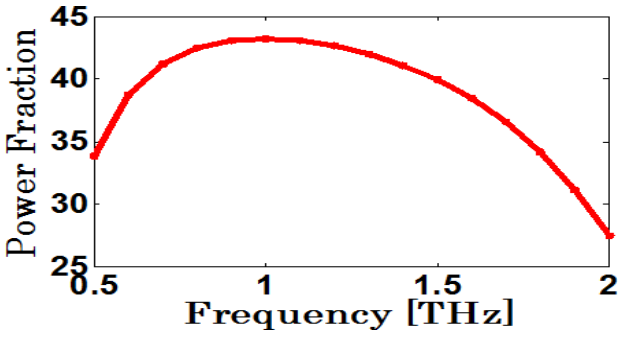


Fig. 8. Power Fraction as a Function of Frequency at Lc=370µm.

4. CONCLUSION

This study presents a novel photonic crystal fiber (PCF) optimized for terahertz (THz) wave guiding, utilizing cyclo-olefin polymer (COP) for enhanced performance compared to traditional materials. The innovative elliptical core design and asymmetrical struts enable effective modal confinement, facilitating improved THz wave propagation.

Simulation results from COMSOL 5.3a confirm that the effective refractive index increases with frequency, demonstrating the design's feasibility for THz applications. Notably, the x-polarized mode exhibits tighter confinement, while the y-polarized mode shows minimal loss, highlighting the influence of design parameters on modal behavior.

These advancements have significant implications for applications in biosensing, medical diagnostics, and security monitoring. Future research will focus on optimizing geometric parameters and integrating this technology into practical sensing systems. Overall, this work contributes valuable insights into THz waveguide technology, supporting the development of efficient communication and sensing devices.

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