Design and Analysis of Photonic Crystal Fiber for Terahertz Communication

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Abstract: Photonic crystal fibers (PCFs) are revolutionizing the field of THz communication. This paper presents a Topas-based PCF design simulated using COMSOL Multiphysics software, that boasts exceptional properties tailored for THz applications. The proposed structure features a rectangular air gap core with integrated square slots, surrounded by a cladding adorned with circular air holes of varying sizes. The meticulously crafted arrangement of these holes forms distinct square lattice structures, each playing a crucial role in optimizing the fiber's performance. At a frequency of 3 THz, the proposed PCF demonstrates a high birefringence of 0.052, ensuring efficient polarization control. Furthermore, it boasts impressively low effective material losses (EML) of 0.071 cm-1 and 0.056 cm-1 for the x and y polarization modes, respectively, minimizing signal attenuation. Remarkably, the confinement losses for both polarization modes are negligible, hovering around 10-10 and 10-11 cm-1, respectively, ensuring efficient signal transmission. The core power fraction further strengthens the design's efficacy, reaching 41.32% and 46.32% for x and y-polarization modes, respectively, signifying efficient energy confinement within the core region. Thus, the simulated result of the proposed PCF design shows the potential of in THz applications.

Keywords: Photonic Crystal Fiber (PCF), Terahertz (THz), Communication, Comsol

1. INTRODUCTION

In recent years, the Terahertz (THz) region of the electromagnetic spectrum, spanning from 0.1 to 10 THz, has garnered significant attention from researchers due to its unique characteristics and promising applications. This region, positioned between infrared and microwave radiation, offers diverse functional uses such as discreet imaging, astronomy, drug sensing, spectroscopy, DNA hybridization, and telecommunications [1-3]. Terahertz waves, also known as T-rays, are non-ionizing and capable of penetrating various non-conducting materials, making them invaluable for applications in biomedical sensing, communication, and non-destructive testing. Despite the remarkable potential of THz radiation, challenges persist in generating, guiding, and utilizing these waves effectively. The existing waveguide systems often encounter absorption loss, path loss, and integration difficulties during freespace propagation. To address these challenges, researchers have explored various metallic and dielectric waveguides, including Bragg fibers, dielectric metal-coated hollow glass tubes, bare metal wires, parallel-plate waveguides, sub-wavelength porous fibers, and single metallic wires [4-6]. Among the different types of waveguides, photonic crystal fibers (PCFs) have gained prominence, particularly porous core PCFs, for their adaptability and optical properties, including high core power fraction, lower effective material loss, lower

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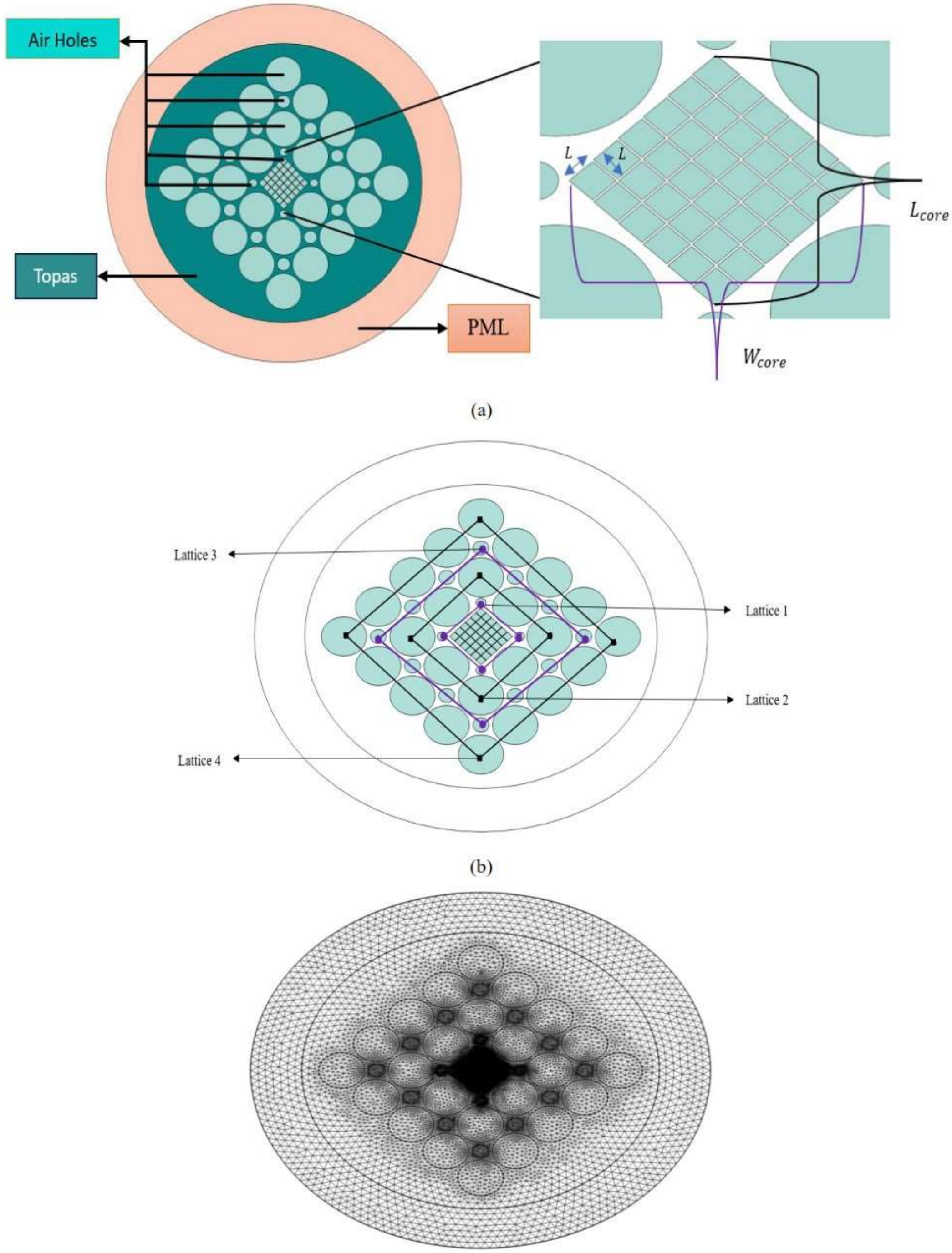
dispersion, high non-linearity, and lower bending loss. Researchers have investigated different PCF structures, such as spiral-shaped PCFs, hexagonal PCFs, rotated hexagonal porous core PCFs, and elliptical core PCFs, to optimize properties like effective material loss, core power fraction, and dispersion [7-9]. Studies have revealed a scope for improvement in PCF designs, addressing challenges like material loss, dispersion, and core power fraction. Recent endeavours include the proposal of novel structures, such as a TOPAS-based hexagonal lattice PCF with an elliptical core, aiming for ultra-low effective material loss and enhanced dispersion properties. The exploration of PCFs extends to considerations of various background materials, such as Zeonex, to optimize dielectric properties for effective THz wave propagation. Advances in PCF design, like the proposed ultra-low material loss singlemode photonic crystal fiber with a circular shape in the cladding and elliptical core made of Zeonex, showcase the ongoing efforts to overcome limitations and enhance the performance of THz waveguides [10-14]. In this context, our research paper contributes to the ongoing discourse by introducing a novel approach, a low material loss single-mode photonic crystal fiber with a square shaped cladding using circular air holes and rectangular core made of integrated square slots. The proposed structure aims to achieve optimal properties, including low effective material loss, a large effective area, and a substantial power fraction in the core area, addressing the existing limitations in THz waveguide technology. The paper is organized as follows: Section II presents the proposed PCF structure, in section III the performance of the proposed structured is analyzed for different parameters in THz spectrum and finally the paper is concluded in Section IV.

2. PROPOSED DESIGN FOR THZ COMMUNICATION

The PCF (Photonic Crystal Fiber) structure design integrates a multi-lattice cladding arrangement characterized by circular air holes forming lattice 2 and lattice 4, with diameters of d_1, and lattice 1 with diameter d_2, while lattice 3 employs a diameter d_3, systematically arranged in square forms as shown in fig. 1(b). Notably, the dimensions adhere to a specific hierarchy: $d_1 > d_3 > d_2$. This composite cladding configuration creates a square-shaped outer structure. Conversely, the inner core comprises of 36 square air holes, each measuring $L \times L$, meticulously arranged to fashion a rectangular-shaped core with dimensions $L_{core} \times W_{core}$ as shown in fig. 1(b). The square air holes are separated from each other by a pitch distance $'\Lambda'$. The dimensions are listed in Table I. The strategic alignment and varying diameters within the lattices optimize the photonic properties and performance of the designed PCF, facilitating enhanced light light guiding capabilities tailored to specific applications. The proposed PCF was simulated using COMSOL v5.6 software, leveraging the Finite Element Method (FEM). To guarantee optimal accuracy, a user-controlled mesh configuration was implemented throughout the simulation process. The complete structure has 24,848 triangular components and 312 vertex elements. To accommodate the varying dimensions of the air holes, a minimum element size of $0.113\mu m$ was utilized and the minimum element quality of 0.5035 is obtained. Fig. 1(c) show the mesh diagram of the proposed PCF design.

The PCF's cladding section is encased in a safeguarding sheath incorporating the Perfectly Matched Layer (PML) boundary condition. This specialized layer serves a dual purpose: augmenting simulation precision while proficiently eradicating external reflections, thereby refining result accuracy. The structural base material, topaz, maintains a consistent refractive index of 1.528 across a frequency spectrum spanning 1.5 to 3 THz. This material choice and index uniformity remain constant throughout the specified frequency range, ensuring stability within the PCF design.



(c)

Fig. 1. Proposed Photonics Crystal Fiber (PCF) structure (a) Cross-Section view (b) Lattice representation formed by air-holes (c) Mesh representation

Table 1. Proposed PCF Structure's air hole dimension

Shape	Dimension
Air holes with dimension, d_1	45 μm
Air holes with dimension, d_2	10 μm
Air holes with dimension, d_3	16 μm
Lenght of square air holes, L	14.142 μm
Length of Core, L_{core}	130 μm
Width of Core, W_{core}	125 μm

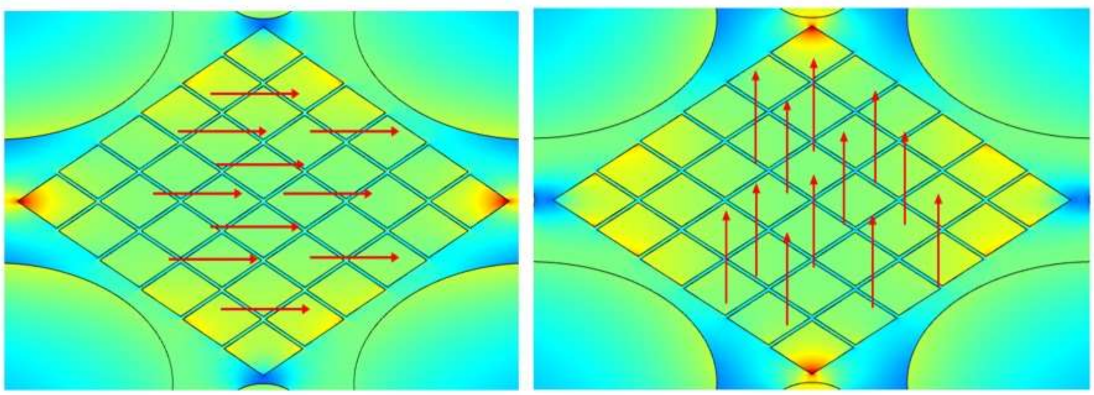


Fig. 2. Field distribution of fundamental mode of the proposed PCF at 2THz (a) x-polarization (b) y-polarization

3. RESULTS AND DISCUSSIONS

The Finite Element Method is employed to conduct a comprehensive numerical analysis of the proposed PCF. An array of distinct PCF attributes—such as "birefringence, effective material loss (EML), core power fraction, effective refractive index and confinement loss —are meticulously examined. This investigation is geared towards comprehensively understanding and assessing the PCF's performance within the THz range. Figure 2 depicts the mode field profiles encompassing both x-polarization and y-polarization, offering a visual representation of the PCF's behaviour in each mode.

3.1. Effective Refractive Index

As the frequency increases, the effective refractive index of the proposed PCF also rises, as illustrated in fig. 3. This is because light within the PCF travels along a specific path, guided by the refractive index profile. At lower frequencies, the core-cladding contrast is strong enough to tightly confine the light. However, as frequency increases, the wavelength of light becomes shorter, and its interaction with the refractive index profile weakens. This allows the mode to "spill over" into the cladding, albeit exponentially decaying away from the core. Specifically, at 3 THz, this fiber demonstrates effective refractive indices of approximately 1.1114 for x-polarization and 1.1567 for y-polarization. Notably, the effective refractive index for y-polarization exceeds that of x-polarization, indicating a more robust confinement of light within the core for y-polarization in comparison to x-polarization.

3.2. Birefringence

Birefringence denotes the "variance in refractive indices between two orthogonally polarized modes" and is expressed as:

$$B = |\eta_x - \eta_y| \tag{1}$$

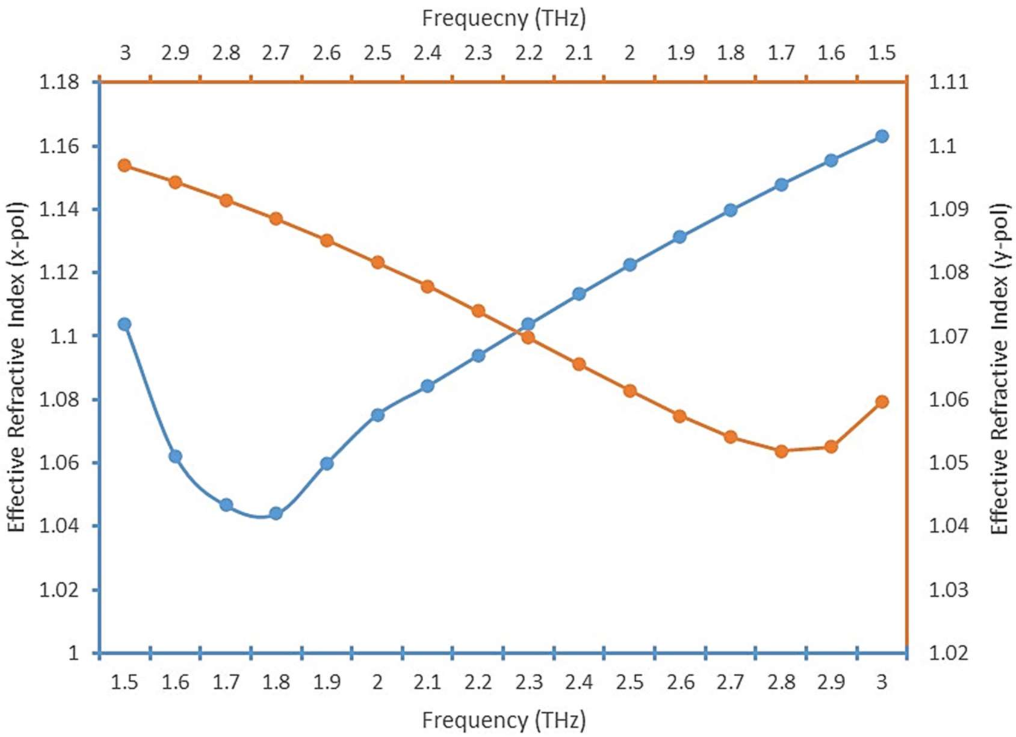


Fig. 3. Effective refractive index vs Frequency

where B represents birefringence and η_x and η_y signify the refractive indices of x and y polarized modes respectively. As illustrated in fig. 4, a distinct trend emerges: birefringence exhibits a steady increase with escalating frequency, reaching its peak around 3 THz, after which it gradually diminishes or stabilizes. This intriguing behavior can be attributed to the substantial disparity in refractive indices between the core and cladding, particularly contributing to the surge in effective refractive index at higher frequencies.

3.3. Effective Material Loss and Confinement Loss

The predominant challenge encountered by terahertz waves within the PCF primarily arises from what's termed as effective material loss (EML), often referred to as material absorption loss (α_{eff}). The quantification of EML in the proposed PCF is denoted through the following expression:

$$\alpha_{eff} = \sqrt{\frac{\epsilon_0}{\mu_0}} \frac{\int_{\text{mat}} \eta_{mat} |E|^2 \alpha_{mat} dA}{\int_{all} S_z dA} \tag{2}$$

In this context, ϵ_0 and μ_0 represent the relative permittivity and permeability of vacuum, respectively. η_{mat} signifies the refractive index of the material, while α_{mat} stands for the absorption loss within the bulk material. Additionally, S_z designates the z-component of the Poynting vector, aligning with the direction of electromagnetic wave transmission. Observing fig. 5, a discernible trend emerges: EML consistently escalates with frequency augmentation. Notably, for the x-polarization mode, the EML surpasses that of the y-polarization mode with increasing frequency. This observed behavior in both modes underscores a shared trait:

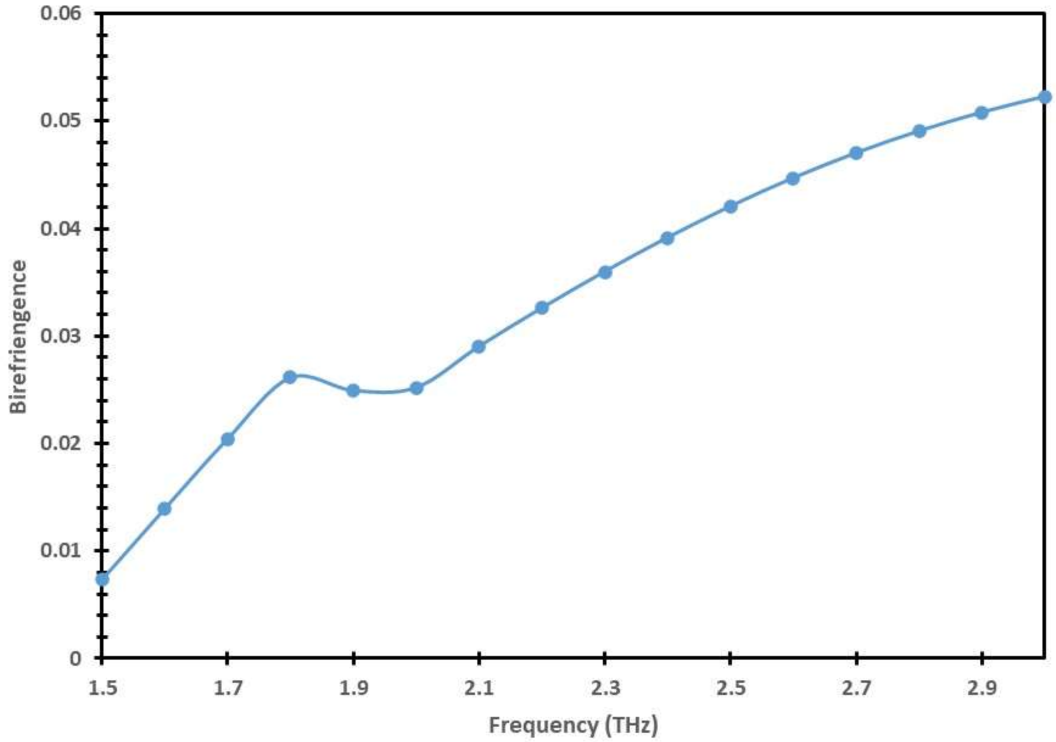


Fig. 4. Illustrating variation of Birefringence with frequency

at lower frequencies, EML remains lower, attributed to a more concentrated confinement of the electromagnetic wave within the core. Confinement loss stands as a pivotal parameter in the design of any PCF, delineating how light attenuation transpires within the core region owing to the specific structure of the photonic crystal fiber, notably featuring air holes within the cladding. The equation presented below encapsulates the correlation between the velocity of light in the waveguide, frequency, and the imaginary component of the effective refractive index:

$$\alpha_{CL} = 8.686 \times \frac{2\pi f}{c} \times Im(\eta_{eff}) \tag{3}$$

Analyzing the fig. 5 for the confinement loss with respect to frequency shows that: with an increase in frequency, there is a concurrent decrease in confinement loss, signifying a stronger confinement of light within the core region. Remarkably, the minimum confinement loss achieved registers at $10^{-10}\ cm^{-1}$ for x-polarization and $10^{-11}\ cm^{-1}$ for y-polarization modes, underscoring the efficacy of light confinement within the PCF's core across different polarizations.

3.4. Core Power Fraction

The Core Power Fraction (CPF) holds significant importance in the realm of THz waveguide design, primarily concerning the evaluation of power transmission within the core of the PC. Within the context of standard THz waveguide configurations, a greater emphasis is placed on achieving a higher CPF. This preference stems from the implication that a higher CPF corresponds to a reduced departure of modal power from the core. This critical parameter

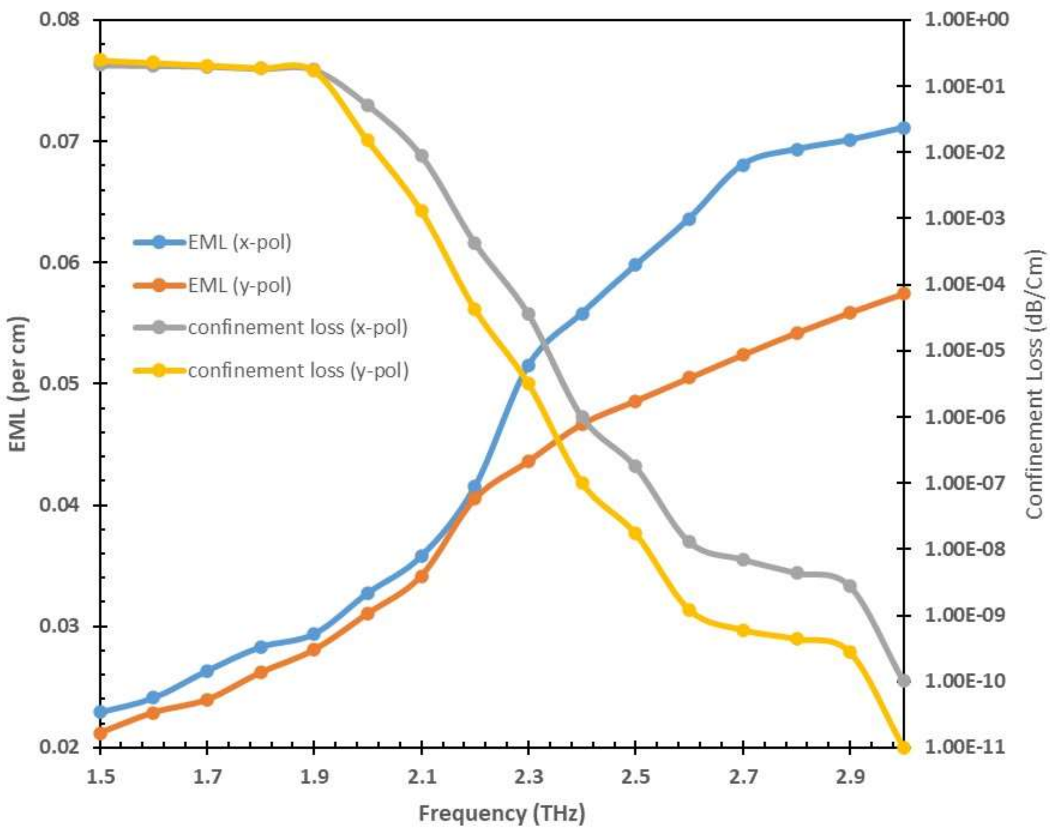


Fig. 5. Showing the variation of EML and confinement loss with respect to frequency for both x-pol and y-pol modes

is derived through a specialized expression, allowing for the precise quantification of power distribution within the waveguide structure.

$$\eta' = \frac{\int_{\text{core}} S_z dA}{\int_{\text{all}} S_z dA'} \quad (4)$$

Denoted as η', this parameter signifies the proportion between the specific area of focus and the entirety of the fiber's overall area. As shown in fig. 6, the core power fraction for y-polarization mode is more than the x-polarization mode. It is also seen that as frequency increase the core power fraction increases. The maximum core power fraction of 46.32% is achieved for y-polarization at 3 THz frequency whereas for x-polarization mode achieves 41.32%.

4. CONCLUSION

In this paper, design of a Topas-based photonic crystal fiber (PCF) has been introduced. This structure features a rectangular shape air gap core integrated with square slots, encircled by a cladding composed of circular air holes of different dimensions. The arrangement of these holes forms distinct lattice structures—circles creating a square lattice of different dimensions. The primary aims of this study encompass achieving low effective mode area

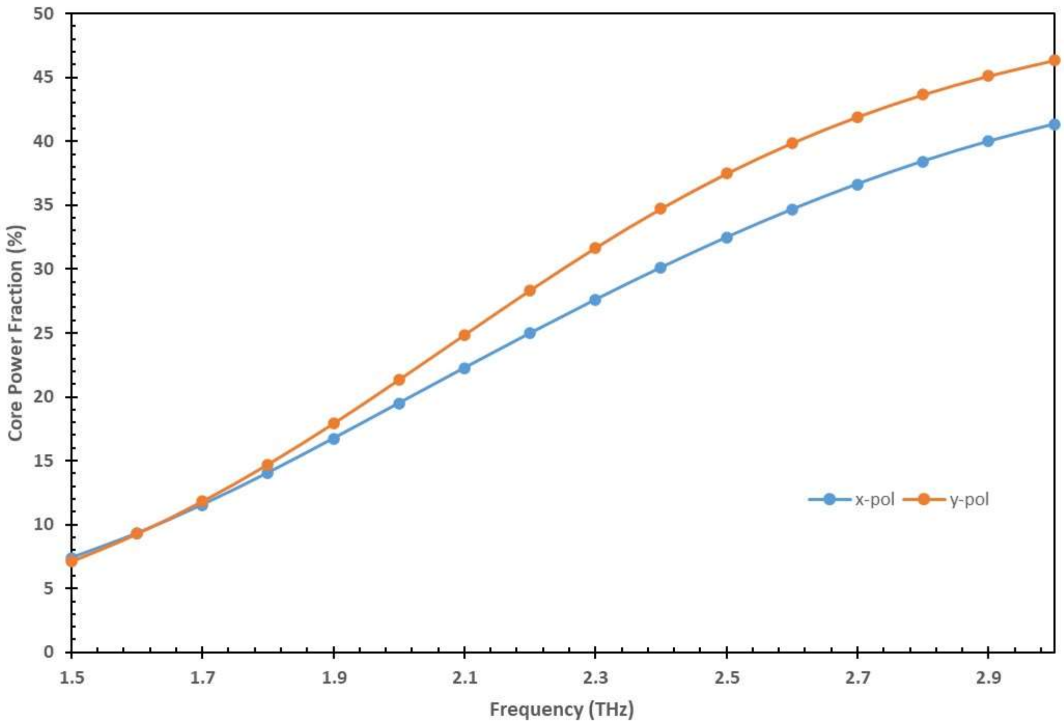


Fig. 6. Core power fraction (%) vs frequency for x-pol and y-pol

(EML), fostering high birefringence, and minimizing confinement loss and core power fraction, all finely tuned for specific frequency range of 1.5 THz - 3 THz. Notably, this proposed PCF structure exhibits significant promise, especially within the realm of THz communication, owing to its unique amalgamation of tailored properties and functionalities. Future research endeavours are poised to delve deeper into various waveguide properties, such as dispersion, spot size, and V-parameter. These investigations will explore their interconnections with varying core diameters and porosities, enhancing the understanding and performance evaluation of this PCF design.

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