Low Effective Material Loss TOPAS Based Single-Mode Photonic Crystal Fiber with High Core Power Fraction in the THz Waveguiding

Selim Hossain

KYAU <https://orcid.org/0000-0003-0715-4873>

Shuvo Sen (✉ shuvombstu.it12009@gmail.com)

Mawlana Bhashani Science and Technology University

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Low effective material loss TOPAS based single-mode photonic crystal fiber with high core power fraction in the THz waveguiding

Md. Selim Hossain¹, Shuvo Sen^{2*}

¹Department of Computer Science and Engineering, Khwaja Yunus Ali University, Enayetpur, Sirajganj, Bangladesh

²Department of Information and Communication Technology (ICT), Mawlana Bhashani Science and Technology University (MBSTU), Santosh, Tangail-1902, Bangladesh

*Corresponding Author: Mawlana Bhashani Science and Technology University, Santosh, Tangail-1902, Bangladesh

Email: shuvombstu.it12009@gmail.com

Abstract

In this study, five layers of hexagonal cladding and two elliptical air holes based on photonic crystal fiber are discussed highly for many communication areas by decreasing different types of losses such as effective material loss (EML), scattering loss, and confinement loss in the terahertz (THz) waveguiding. Our suggested fiber (H-PCF) and all simulation results are obtained with the finite element method (FEM) and the perfectly matched layer (PML) boundary conditions based COMSOL Multiphysics software have been used to design in the THz region. After investigating all the graphical results, this optical communication-related H-PCF fiber discloses an extremely low effective material loss (EML) of 0.0184 cm^{-1} , with an effective area of $7.07 \times 10^{-8} \text{ m}^2$ and flow of power in the core region of 88% at 1 terahertz (THz). Here, other simulation parameters such as confinement loss, scattering loss, and V-parameter are also presented with a proper graph. So, we can easily say that the reported H-PCF fiber is strongly appropriate for different types of short and long-distance communication applications in the terahertz (THz) wave pulse region.

Index Terms— Scattering loss, Confinement loss, Low effective material loss, Single Mode H-PCF, Communication in terahertz optical Fiber.

Introduction

Nowadays, researchers are trying to investigate the high-level research work on wireless communication systems at THz frequency to increase more capacity compared to the previous system. Terahertz (THz) radiation which changing from 0.1 to 10 THz has gained considerable interest due to its numerous functional uses related to electromagnetic radiation [1-2]. The assortment of THz frequency exists between the microwave and infrared radiation (IR) in the

electromagnetic range. The THz frequency range shows the fascinating development in the field of sensing [3], spectroscopy [4], pharmaceutical drug testing [5], biomedical sensing [6], telecommunications [7], weapons in a non-destructive way [8], DNA Hybridization [9], etc. The leading sources of THz radiation are high-frequency Gunn diodes, far-infrared (FIR) gas laser, quantum cascade laser (QCL), free-electron laser, etc. Moreover, Schottky barrier diodes, pair braking detectors, hot electron mixers, field-effect transistor detectors, Bolometers, etc. are the fundamental T-ray detector. The necessity of high bandwidth in wireless schemes has been increased due to the unoccupied bandwidth for the current communication scheme. The transmission scheme of THz frequency largely depends on the free space medium but most of the THz waveguides experience an unavoidable absorption loss, path loss, difficult integration with other components during free-space propagation [10].

Over the last few years, some metallic and dielectric waveguides for the THz spectrum have been reported such as Bragg fibers [11], dielectric metal-coated hollow glass tubes [12], bare metal wires [13], parallel-plate waveguides [14], sub-wavelength porous fibers [15], single metallic wires [16], plastic ribbon waveguides [17]. Recently, porous core photonic crystal fibers (PCFs) have obtained significant interest because of their versatility in structural nature and desirable optical guiding properties such as high core power fraction, lower effective material loss, lower dispersion, highly birefringence, high nonlinearity, lower bending loss. Total internal reflection (TIR) and photonic bandgap (PGB) are two basic optical guiding properties are found in PCF. If the light is confined in a higher region of the refractive index in solid-core PCF then the total internal reflection can be optimized. Numerous polymers have been used as background materials in microstructure core PCF to control the optical guiding properties such as TOPAS, Tellurite, Zenox, poly methyl-methacrylate (PMMA), Graphene, Teflon [18-23], etc.

To get a higher sensitivity across the EM spectrum, many standard articles regarding PCFs have already been investigated. Islam et al. [24] anticipated a porous-core spiral shape photonic crystal fiber (PCF). Their proposed model obtained the EML and EA of 0.1 cm^{-1} and $1.82 \times 10^{-7} \text{ m}^2$ accordingly at 1 THz frequency. But their proposed model showed higher EML. In 2016, Hasan et al. [25] explored hexagonal PCFs that gained EML of 0.089 cm^{-1} at 1 THz frequency. Saiful et al. [26] suggested a rotated hexagonal porous core with circular shape

cladding and obtained an EML of 0.053 cm^{-1} with a dispersion of 0.25 ps/THz/cm . In 2018, Rana et al. [27] proposed a hexagonal-shaped hole combined within the core of a Kagome lattice PCF. Their proposed model displays EML of 0.029 cm^{-1} and core power fraction of 33% at 1.3 THz frequency. In the same year, Sultana et al. [28] designed a hexagonal shape cladding with elliptical core PCF obtain EML of 0.05 cm^{-1} and very high birefringence of 0.086. From the previous background, we have got comparably higher EML and some important aspects such as power fraction (PF) and bending loss were not explored. An elliptical core PCF with kagome lattice cladding where EML of 0.056 cm^{-1} and lower dispersion of $0.27 \pm 0.18 \text{ ps/THz/cm}$ 1 THz operating frequency was anticipated in 2019 by Saiful [29].

In this paper, we have designed a TOPAS based hexagonal shape of PCF with an elliptical core has been introduced in the THz regime. The proposed model shows a low EML of 0.0184 cm^{-1} with 80% core power fraction and a large effective area of $7.07 \times 10^{-8} \text{ m}^2$ at 1 THz optical frequency.

Design Methodology

The cross views of H-PCF are exposed in Fig. 1. where Λ_1 and d_1 are defined by the pitch and diameter of our design concept. The constraints d_1/Λ_1 is called the air filling ratio and this ratio tries to guard against collapse between two AHs and the background material of TOPAS helps to reduce many types of losses. Λ_c , d_a and d_b constraints are called the pitch and diameters of the two elliptical AHs similarly. Here, we find the numerical properties such as effective area, scattering loss, V-parameter, EML, fiber power fraction, and confinement loss of the fiber in the THz region with the COMSOL Multiphysics software. The optimum constraints are cladding diameter $d_1 = d_2 = d_3 = d_4 = d_5 = 300 \text{ }\mu\text{m}$, cladding pitch $\Lambda_1 = \Lambda_2 = \Lambda_3 = \Lambda_4 = \Lambda_5 = 400 \text{ }\mu\text{m}$, core diameter $d_a = 52 \text{ }\mu\text{m}$, $d_b = 167 \text{ }\mu\text{m}$ and core pitch $\Lambda_c = 100 \text{ }\mu\text{m}$.

Fig. 1: Pictorial views of H-PCF along with (a) Cladding region (b) Core region and (c) Mode field distribution.

Numerical Analysis:

Background material (TOPAS) has been used of this suggested H-PCF fiber to reduce the effective material loss (EML). Here, EML α_{eff} is premeditated by [31]:

$$\alpha_{\text{effective}} = \sqrt{\frac{\epsilon_0}{\mu_0}} \left(\frac{\int_{\text{mat}} n_{\text{mat}} |E|^2 \alpha_{\text{mat}} dA}{|\int_{\text{all}} S_z dA|} \right) (\text{cm}^{-1}) \quad (1)$$

Where, α_{mat} is the bulk material absorption loss and n_{mat} is the RI of the material. ϵ_0 is the relative permittivity and the permeability of free space is μ_0 . $S_z = \frac{1}{2} (\mathbf{E} \times \mathbf{H}^*)$. z is the pointing vector, where, z is component of S_z , E and H^* are electric field apparatuses and the complex couple of the magnetic field.

SL of H-PCF fiber is thought-out by the subsequent equation [32]:

$$\alpha_R = C_R \times \left(\frac{f}{c}\right)^4 \text{ (dB/km)} \quad (2)$$

Where, C_R is called the scattering coefficient.

The low confinement loss-based PCF fiber is highly used for different types of communication sectors. Here, the confinement loss L_c is calculated the equation [33]:

$$L_c = 8.686 \times K_0 \text{Im} [n_{\text{eff}}] \text{ (dB/m)} \quad (3)$$

Where, $K_0 = \left(\frac{f}{c}\right)$ is the free wave number, f is the frequency and c are the speed of photon. $\text{Im} [n_{\text{eff}}]$ is the imaginary part of ERI.

In H-PCF fiber, the principal part is formed by the effective mode area (EMA). Here, the EMA is figured by [34]:

$$A_{\text{effective}} = \frac{[\int I(r,t) r t d r t]^2}{[\int I^2(r,t) d r t]^2} \quad (4)$$

Where, $A_{\text{effective}}$ is the EMA and $I(r,t) = |E_r|^2$ is the cross-sectional electric field intensity.

Power fraction (PF) is resulted by the total power through the H-PCF fiber. So, the PF η is intended by [34]:

$$\eta = \frac{\int_i S_z dA}{\int_{\text{all}} S_z dA} \quad (5)$$

V-parameter describes the mode propagation of the H-PCF structure. So, V-parameter is restrained by the following equation [35]:

$$V = \frac{2\pi r f}{c} \sqrt{n_{\text{co}}^2 - n_{\text{cl}}^2} \leq 2.045 \quad (6)$$

Where, the core radius is r , n_{co} and n_{cl} are signed by the EMI of the core and cladding area.

Analysis of Numerical Results and Discussions:

COMSOL Multiphysics software has been used to compute entirely optical properties and graphical results from Fig. 2 to Fig. 9 of this the recommended H-PCF are premeditated from 0.8 to 3 THz frequency range. The effective area of the designed PCF is illustrated in figure 2 according to the frequency changing from 1.00 THz to 3.00 THz for 60%, 70%, and 80% porosities. The effective mode area is pragmatic to be decreased gradually that shown in Fig. 2.

The effective area is computed as $7.07 \times 10^{-8} \text{ m}^2$, $7.14 \times 10^{-8} \text{ m}^2$, and $7.32 \times 10^{-8} \text{ m}^2$ for 80%, 70% and 60% porosities respectively.

Fig. 2: EA according to the diverse frequencies such as 80%, 70% and 60% porosities.

Fig. 3 explain the EA in accordance with core diameter (D_{core}) for 60%, 70% and 80% porosities at 1 THz. For optimum core diameter $D_{\text{core}} = 324 \mu\text{m}$, effective area is computed as $8.12 \times 10^{-8} \text{ m}^2$, as $8.38 \times 10^{-8} \text{ m}^2$ and as $8.74 \times 10^{-8} \text{ m}^2$ for 80%, 70% and 60% porosities correspondingly for 1 THz working frequency.

Fig. 3: Effective area according to the different core diameters such as 80%, 70% and 60% porosities.

Fig. 4 proves the frequency based effective material loss (EML) graph for several porosities. The figure specifies that the EML of proposed structure decreases with the increasing of frequency over 0.08 THz to 3 THz in electromagnetic spectrum assortment.

Fig. 4: EML according to the frequency such as 80%, 70% and 60% porosities.

Therefore, increasing of core porosity of PCF, the generated electromagnetic wave interacts with limited amounts of material; the EML of the proposed fibers then decreases. For optimum design conditions at 1 THz frequency, the EMLs are 0.0184 cm⁻¹, 0.0156 cm⁻¹, and 0.0137 cm⁻¹ for 80%, 70% and 60% porosities correspondingly.

EML due to the changes in core diameter (D_{core}) of proposed model with 60%, 70% and 80% porosities have been shown in Fig. 5 at 1 THz frequency. The increases of core diameter the EML is decreasing gradually at optimum design parameter. In our proposed PCFs $D_{\text{core}} = 324 \mu\text{m}$ the EML is about 0.0184 cm⁻¹ for 80% core porosity which is optimum value and not production any complexity in fabrication. At a constant value of D_{core} , the proposed model shows the different values of EML for different porosities.

Fig. 5: EML according to the core diameters such as 80%, 70% and 60% porosities.

Fig. 6 indicates the distribution of power across the core, cladding and materials in accordance with frequency at a fixed $D_{\text{core}} = 324 \mu\text{m}$. The experimental frequency varieties within 0.08 THz to 3 THz in electromagnetic spectrum. As it was found that, 80% optical power generated through the fiber core at frequency 1 THz which means maximum light contact with analytes in the core region. Furthermore, the air holes in cladding region induced light waves to pass within the core and provide maximum core power fraction. The pragmatic power fraction is significantly higher than the previously stated article.

Fig. 6: Power fraction according to the different frequencies for optimum constraints.

Fig. 7 proves the scattering loss analysis for the variations in wavelength in proposed structure. Scattering loss is an important parameter because it contributes the total losses of the fiber. Scattering loss is increasing with the increases of frequency within 0.08 to 3 THz range appeared in Fig. 7 where's the $D_{\text{core}} = 324 \mu\text{m}$. The gained scattering loss of proposed PCF is 1.236×10^{-10} dB/km at optical wavelength 1 THz which is negligible.

Fig. 7: Scattering loss according to the different frequencies for optimum design parameters.

Fig. 8 illustrates the behavior of CL with respect to frequency at optimum design parameter. Confinement loss (CL) of proposed model is being reduced due to rising of frequency across 0.08 to 3 THz at $D_{\text{core}} = 324 \mu\text{m}$. When light passes through the core with high frequency then it improves the index contrast of core and cladding and thus minimize the confinement loss. It is observed that the confinement loss of proposed structure at optimum design constraints for 1 THz of the order of 3.36×10^{-15} dB/m.

Fig. 8: Confinement loss according to the different frequencies for optimum design parameters.

V_{eff} is explored as the function of frequency for optimum design constraint at $D_{\text{core}} = 416 \mu\text{m}$ which has been revealed in Fig. 9. Her, the optimum constraints are cladding diameter $d_1 = d_2 = d_3 = d_4 = d_5 = 300 \mu\text{m}$, cladding pitch $\Lambda_1 = \Lambda_2 = \Lambda_3 = \Lambda_4 = \Lambda_5 = 400 \mu\text{m}$, core diameter $d_a = 52 \mu\text{m}$, $d_b = 167 \mu\text{m}$ and core pitch $\Lambda_c = 100 \mu\text{m}$.

Fig. 9: V-parameter according to the different frequencies for optimum design parameters.

The designed H-PCF shows outstanding EML, confinement loss, core power fraction, and effective area belongings than other designed PCFs at 1 THz functional frequency as providing in Table 1.

Table 1: Propagation comparison among Prior PCFs and of the proposed H-PCF.

Ref.	EML (cm^{-1})	Porosity (%)	Power Fraction	Confinement Loss (dB/m)	Effective Area (A_{eff} (m^2))
[36]	0.110	-	-	-	0.98×10^{-07}
[37]	0.100	30	-	1.0×10^{-01}	2.3×10^{-07}
[38]	0.1	-	32.5%	-	-
[39]	0.085	-	37%	-	-
[40]	0.05	-	67.05%	-	-
[41]	0.063	-	46%	-	-
[42]	0.089	60	37%	1.0×10^{-02}	9.77×10^{-08}
[43]	0.076	80	53%	8.96×10^{-01}	-

[44]	0.068	50	-	-	-
[45]	0.050	60	42%	1.00	-
Proposed H-PCF	0.007	84	80%	3.37×10^{-14}	3.46×10^{-8}

It has been found Table 1 which shows better outputs compare to the former research work. We have found EML 0.007 cm^{-1} , power fraction 80%, Confinement loss $3.37 \times 10^{-14} \text{ dB/m}$ and effective area is $3.46 \times 10^{-8} \text{ m}^2$.

Conclusion:

An excellent design of five layers hexagonal cladding area based CAHs and two elliptical AHs in the core region are offered for communication applications with decreasing different types of losses such as EML, confinement loss, and scattering loss. TOPAS has been used as background material to remove different losses compare to the previous research work. Moreover, our designed H-PCF structure are designed with the procedure of FEM and PML conditions based on COMSOL Multiphysics software to get the simulated data. The graphical results of this H-PCF fiber show an ultra-low effective material loss (EML) of 0.0184 cm^{-1} , the larger effective area of $7.07 \times 10^{-8} \text{ m}^2$, power moving in the core region of 88%, low confinement loss of $3.36 \times 10^{-15} \text{ dB/m}$, and scattering loss of $1.236 \times 10^{-10} \text{ dB/km}$ respectively at 1 THz. So, after investigating all the simulation results, we can say strongly that our H-PCF fiber will be highly appropriate for numerous communication areas in the terahertz (THz) regime.

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

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