Design and analysis of heptagonal cladding with rotated-hexa elliptical core based PCF for the applications of communication sectors in the THz region

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Abstract
Photonic crystal fiber-based heptagonal cladding with the elliptical rotated-Hexa core is reported in the terahertz waveguide for the applications of communication area in this paper. By utilizing the photonic crystal fiber concept, all numerical results have been obtained by the finite element method with perfectly matched layers based on the COMSOL Multiphysics computer software tool. This H-PCF fiber shows a low effective material loss of 0.0076 cm⁻¹, with a larger effective area of 5.95×10⁻⁸ m², power flows within the core area of 90%, confinement loss of 3.35×10⁻¹⁶ cm⁻¹, and scattering loss of 1.24×10⁻¹⁰ cm⁻¹ at 1 THz. Besides, other optical properties like confinement loss, scattering loss, power fraction, V-parameter, and effective area have also been considered briefly. So, it is expected that the mentioned H-PCF structure-based waveguide will significantly improve many kinds of communication fields of the THz technology.

Keywords Scattering loss · Confinement loss · Effective material loss · Heptagonal cladding · Birefringence · Numerical Aperture, etc.
1 Introduction

Recently, Terahertz radiation or spectrum, which varies from 0.1 to 10 THz, has gained significant interest owing to its numerous practical applications. The gray area lies within the context of the infrared radiation and microwave spectrum. The enormous THz frequency is potential in diverse areas like sensing (Islam et al. 2017a, b), biomedical imaging (Hossain et al. 2021a), communications (Pinto and Obayya 2007), biotechnology (Nagel et al. 2002), time-domain spectroscopy (Vigneswaran et al. 2018), salinity (Amiri et al. 2018), temperature sensor (Selim Hossain and Kamruzzaman, 2021), security screening (Islam et al. 2016a) applications. It also provides significant developments in the origins and identification methods of the THz wave. The entire THz system consists of three distinct parts, like the sources of THz, wave guidance, and sensor. Among them, THz source and detector are available commercially. The THz sources and detectors are rapidly upgraded with the support of advanced modern technology. The most significant THz sources are Gunn diodes, free-electron lasers, quantum cascade lasers, organic gas far-infrared laser, etc. Besides, Bolometer, Golay Cell, Pyroelectric detector, Schottky barrier diodes are the most usable T-ray detector. However, due to frequency propagation, most THz waveguides largely depend on free-space wave propagation. But the free space wave propagation faces some problems such as path loss, material loss, and high absorption loss. To minimize these problems, the researchers had already proposed various waveguides because of the successfull propagation of the THz wave. These are Bragg fibers (Jeon et al. 2005), Metallic waveguides (Wang and Mittleman 2004), Silver coated hollow glass (Bowden et al. 2007; Skorobogatyi and Dupuis 2007), subwavelength waveguide (Hassani et al. 2008), parallel-plate waveguides (Chen et al. 2006), etc. Uses of metallic waveguides in THz transmission can face difficulties like high bending loss and frequency-dependent losses. Bragg fibers offer better efficiency in dispersion and filtering applications. Still, in practical wavelength division multiplexing applications, it is challenging to obtain desirable output by using Bragg fibers. Parallel-plate waveguide’s main limitation is confinement loss.

Microstructure core PCF recently exhibits advanced structural flexibility and highly high optical properties. A significant advantage is that maximum optical power passes across the core region that helps to reduce material loss. Two basic optical guiding properties are commonly found in microstructure core PCF: modified total internal reflection (MTIR) and the other is photonic bandgap (PBG). The photonic bandgap function works in PCF when the cladding’s refractive index (RI) is greater than the core RI. Conversely, when the core RI is larger than cladding, the MTIR impact comes into operation. In THz guiding medium, microstructure PCF is proposed to obtain lower confinement loss, highly numerical aperture, lower dispersion, highly birefringence, and better waveguiding properties. By using solid materials in the core region, PCF experiences high material losses. A porous air core is preferred across a solid body (Tang et al. 2013). Such properties are helpful to utilize porous polymer PCFs as in different filtering and sensing applications. Other types of background materials such as ZEONEX, TOPAS, Teflon, PMMA (Polymethyl methacrylate), ZBLAN (Yuan et al. 2011; Bulbul et al. 2020; Hossain et al. 2021b; Jiang et al. 2015; Dash and Jha 2014) are being used to increase the optical guiding properties and minimize the effective material loss. We use TOPAS as the background material because it exhibits some excellent optical properties such as the lower material loss, high temperature insensitive, low dispersion and constant refractive index over the 0.1–2 THz frequency range (Hossain et al. 2021c). The researchers mainly focus on reducing effective material loss with scattering loss and maximizing the core power fraction in THz wave-based PCF.
In 2012, Bao et al. (2012) proposed porous-core honeycomb bandgap THz fibers, which show higher EML and coupling loss of 0.35 cm$^{-1}$ and 5 dB, respectively. Their proposed structure EML is very high. Later, Islam et al. (2015a) introduced a spiral shape PCF which achieved efficient area, and EML is $1.82 \times 10^{-7}$ m$^2$ and 0.10 cm$^{-1}$ accordingly at 1 THz frequency range. Through obtained EML is high and did not show two essential factors as V-parameter and power fraction. Moreover, Hasanuzzaman et al. (2015) proposed kagome lattice structure PCF and decreased the EML to 0.035 cm$^{-1}$ with a dispersion difference of 0.13955 ps/THz/cm. But their proposed structure is nearly challenging to fabricate. In that context, Islam et al. (2016b) proposed a system built in a circular lattice with a hexagonal core and achieved an EML of 0.047 cm$^{-1}$ with a dispersion variance of 0.15 ps/THz/cm. Sultana et al. (2019) proposed a Zeonex based kagome structured cladding and hexagonal shaped core PCF with an EML of 0.04 cm$^{-1}$ and dispersion of $\pm 0.09$ ps/THz/cm at 1 THz. Very recently, in 2020, another micro-structure PCF structure named THz wave propagation quasi-pattern was introduced by Paul and Ahmed (2020a); their oriented model obtains EML of 0.038 cm$^{-1}$ with an optimum frequency of 1 THz. Bulbul et al. (2021) proposed a rectangular PCF and showed a high EML and dispersion of $0.1176 \pm 0.0112$ ps/THz/cm at 1 THz. After comparing the previous suggested articles (Bao et al. 2012; Islam et al. 2015a,2016b; Hasanuzzaman et al. 2015; Sultana et al. 2019; Paul and Ahmed 2020a; Bulbul et al. 2021), there is an enormous scope to design and modifying PCF sensors in the THz frequency region to achieve the best optical guidance properties.

This article introduced H-PCF for THz wave propagation, and TOPAS is used as the background material for our proposed model. The proposed H-PCF exhibits outstanding optical properties as well. The presented model displays lower effective material loss of 0.0076 cm$^{-1}$ and gained maximum core power fraction of 90% with a larger effective area of $5.95 \times 10^{-8}$ m$^2$, lower confinement loss of $3.35 \times 10^{-16}$ cm$^{-1}$, and lower scattering loss of $1.24 \times 10^{-10}$ cm$^{-1}$ at the frequency of 1 THz.

2 Design methodology

The cross-view of PCF is uncovered in Fig. 1 where P1 and m1 are characterized by the pitch and diameter of our plan concept. The parameters d1/A1 are called the air filling proportion, and this proportion tries to watch against collapse between two air holes in the cladding area. Ac, da, and db parameters are called the pitch and diameters of the elliptical air hole in the core area. At the elliptical rotated-Hexa core territory, the first layer of 6 circular air holes contains a 20°, 80°, 140°, 200°, 260°, 320° angles and the second layer of 12 circular air holes contain a 20°, 50°, 80°, 110°, 140°, 170°, 200°, 230°, 260°, 290°, 320°, 350°. Here, we discover the numerical properties such as confinement loss, scattering loss, power fraction, effective area, effective material loss, V-parameter of the fiber within the THz wave pulse with the COMSOL Multiphysics software. The ideal parameters are cladding distance across $d_1 = d_2 = d_3 = d_4 = 299$ μm, cladding pitch $A_4 = A_5 = A_3 = A_4 = A_5 = 355$ μm, core distance across $d_a = 54$ μm, $d_b = 56$ μm and core pitch $A_c = 60$ μm.

In Fig. 1c, we visualize that the full lights pass through the core areas strongly for modes of x, y polarization. Consequently, we get the low effective material loss for both polarizations of modes at the operating region of 1 THz.
2.1 Numerical analysis

TOPAS is a background material that has been utilized in this PCF fiber to diminish the effective material loss. Here, EML $\alpha_{\text{eff}}$ is premeditated through (Hossain and Sen 2020):
\[ \alpha_{\text{effective}} = \sqrt{\frac{\varepsilon_0}{\mu_0}} \left( \frac{\int_{\text{mat}} n_{\text{mat}} |E|^{2} |dA|}{\int_{\text{all}} S_z dA} \right) \text{(cm}^{-1}) \]  

where, \( \alpha_{\text{mat}} \) is the bulk material absorption loss and \( n_{\text{mat}} \) is the RI of the material. \( \varepsilon_0 \) is the relative permittivity and the permeability of free space is \( \mu_0 \). \( S_z = \frac{1}{2} (E \times H^*) \). \( z \) 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.

Scattering loss of this PCF fiber is thought-out by the subsequent equation (Mou et al. 2019):

\[ \alpha_R = C_R \times \left( \frac{f}{c} \right)^4 \text{(cm}^{-1}) \]  

where, \( f \) is the frequency, \( c \) is the speed of photon and \( C_R \) 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 (Raonaql Islam et al. 2015):

\[ L_c = 8.686 \times K_0 \text{Im}\left[ n_{\text{eff}} \right] \text{(cm}^{-1}) \]  

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

In this PCF fiber, the principal part is formed by the effective area. Here, the effective area is figured by Pennetta et al. (2019):

\[ A_{\text{effective}} = \frac{\left[ \int I(\tau) r d\tau \right]^2}{\left[ \int I^2(\tau) d\tau \right]^2} \]  

where, \( A_{\text{effective}} \) is the EMA and \( I(\tau) = |E_{\text{eff}}|^2 \) is the cross-sectional electric field intensity.

Power fraction is resulted by the total power through this PCF fiber. So, the power fraction \( \eta \) is intended by Nagel et al. (2002):

\[ \eta = \frac{\int S_z dA}{\int_{\text{all}} S_z dA} \]  

V-parameter describes the mode propagation of this PCF structure. So, V-parameter is presented by the following equation (Paul and Ahmed 2019):

\[ V = \frac{2\pi rf}{c} \sqrt{n_{\text{co}}^2 - n_{\text{cl}}^2} \leq 2.045 \]  

where, the core radius is \( r \), \( n_{\text{co}} \) and \( n_{\text{cl}} \) are signed by the effective mode index of the core and cladding area.

The ERI of the PCF directly influences the dispersion profile. The \( \beta \) is the modal propagation constant. It can be acquired from the second order of Taylor expansion that is shown in Paul and Ahmed (2019):

\[ \beta_2 = \frac{2}{c} \frac{dn_{\text{eff}}}{d\omega} + \frac{\omega}{c} \frac{d^2n_{\text{eff}}}{d\omega^2}, \text{[ps /THz/cm]} \]
where, $N_{\text{eff}} = \text{Re} (\beta) \omega/c$ and $\omega = 2\pi f$; For propagation mode, there are found two polarizations (x and y polarizations).

### 2.2 Result analysis and discussions

Here, we have selected the optimum porosity among 66%, 70%, and 74% because from Figs. 2, 3, 4, 5, 6, 7, 8, 9, 10, 11 and 12, it is clearly seen that the total amount of lights transmits within the core area. As a result, this H-PCF fiber shows better graphical results about of optical properties like as low effective material loss, low scattering loss, larger effective area, high core power fraction, better V-parameter, low confinement loss with the frequency ranges from 0.08 to 3 terahertz.

COMSOL Multiphysics program is used to determine completely graphical results from Figs. 2, 3, 4, 5, 6, 7, 8 and 9 of the proposed H-PCF structure from 0.8 to 3 THz. The
**Fig. 4** Effective material loss according to the frequency for 66%, 70% and 74% porosities

**Fig. 5** Effective material loss according to the core diameters for 66%, 70% and 74% porosities

**Fig. 6** Power fraction according to the different frequencies for optimum parameters
Fig. 7 Scattering loss according to the different frequencies for optimum design parameters

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

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

Fig. 10 Birefringence according to the different frequencies for optimum design parameters
effective area is decreased with the increase of frequency from 0.8 to 3 THz for 74%, 70%, and 66% porosities. The EA is measured as $5.95 \times 10^{-8} \text{ m}^2$, $6.17 \times 10^{-8} \text{ m}^2$, and $6.10 \times 10^{-8} \text{ m}^2$ for 74%, 70%, and 66% porosities individually.

Figure 3 shows the effective area in agreement with core diameter ($D_{\text{core}}$) for 74%, 70%, and 66% porosities at 1 THz. Here, the effective area is decreased according to the increasing of the core diameter ($D_{\text{core}}$). For optimum core diameter $D_{\text{core}} = 400 \mu\text{m}$, effective area is presented as $8.12 \times 10^{-8} \text{ m}^2$, as $8.34 \times 10^{-8} \text{ m}^2$ and as $8.64 \times 10^{-8} \text{ m}^2$ for 74%, 70%, and 66% porosities for 1 THz frequency.

Figure 4 shows the effective material loss with the frequency. Here, it is seen that the effective material loss decreases with the increase of frequency wave ranges from 0.8 THz to 3 THz. For optimum design parameters, the effective material losses (EML) are 0.0076 cm$^{-1}$, 0.0069 cm$^{-1}$, and 0.0136 cm$^{-1}$ for 74%, 70% and 66% porosities correspondingly at 1 terahertz frequency.

Figure 5 indicates the effective material loss with the core diameters for 66%, 70%, and 74% porosities. Here, the effective material loss is decreased according to the increase of core diameters. On the other hand, for $D_{\text{core}} = 400 \mu\text{m}$, the effective material loss is approximately 0.0076 cm$^{-1}$ for 74% core porosity and the frequency $f = 1 \text{ THz}$ at optimum design parameters.
Figure 6 shows the core, cladding, and material power fraction in agreement with the frequency ranges from 0.8 to 3 terahertz. Here, it is also seen that the highest amount of power (lights) passes in the core regions. So, the power fractions of core, cladding, and materials are 90%, 1%, and 17%, correspondingly according to the frequency of 1 terahertz at the optimum design parameters.

Figure 7 demonstrates the scattering loss examination for the varieties in frequencies in the proposed structure. Here, the scattering loss is slightly increased with the increases of frequency from 0.08 THz to 3 THz. The scattering loss is achieved for 74% porosity of $1.24 \times 10^{-10} \text{ cm}^{-1}$ at an optical wavelength of 1 terahertz frequency.

Figure 8 outlines the conduct of confinement loss concurring to recurrence at ideal plan parameters. Confinement loss is being diminished due to the rising of operating frequencies from 0.8 to 3 THz at the optimum core diameter value of $D_{\text{core}} = 400 \mu\text{m}$. The confinement loss of expected development at optimum plan parameters for 1 THz of $3.35 \times 10^{-16} \text{ cm}^{-1}$.

V-parameter is explored as the function of frequency for optimal enterprise constraint at $D_{\text{core}} = 400 \mu\text{m}$, as shown in Fig. 9. Here, it is seen that the V-parameter is increased according to the frequency. Moreover, it is also seen that the value of the V-parameter throughout the entire operating frequency range remains 1.02 at an operating frequency of 3 terahertz (THz). Thus, the proposed H-PCF shows in single-mode communication applications (SMF $\leq 2.405$). On the other hand, from Fig. 6, 7, 8 and Fig. 9, the optimum parameters are cladding distance across $d_1 = d_2 = d_3 = d_4 = d_5 = 299 \mu\text{m}$, cladding pitch $A_1 = A_2 = A_3 = A_4 = A_5 = 355 \mu\text{m}$, core distance across $d_a = 54 \mu\text{m}$, $d_b = 56 \mu\text{m}$ and core pitch $A_c = 60 \mu\text{m}$.

The suggested PCF’s significant birefringence is one of its intriguing features. The modal birefringence may be demonstrated in Fig. 10, which calculates the effective refractive indices using FEM. Detailed research is carried out into the birefringence properties of the proposed PCF and the influence of structural factors. It is noticed that with the rise in the value, the modal birefringence is higher, and the birefringence value is $1.7 \times 10^{-6}$. With additional optimizing settings, the suggested PCF can tune the birefringence up to a one magnitude order.

The numerical aperture controls how much fiber core optical light is captured. This is why the number opening is also known as the zone for the gathering of light. It’s a parameter without units. Optical light is supported by the numerical aperture at the receiver portion. The high numerical aperture is enormously demanded in the communication and sensing field via optical fiber and may be achieved if the resultant difference is excellent between the core area and the recessed region. The following equations can find the NA of the proposed PCF.
Figure 11 depicts the numerical aperture with a frequency profile spanning from 0.20 THz to 0.55 THz. It also demonstrates that as the frequency increases, the numerical aperture decreases. Because all of NA’s curves pass through a small region, a zoom view part is also presented.

Figure 12 illustrates well that both polarization curves exert themselves to the left and the right with close-fitting behavior. A flat dispersion of 0.97 THz to 1.09 THz near zero has been observed in a larger frequency spectrum.

In some cases, multiple optical signals with almost the same pulse spread can be transmitted simultaneously. The lower dispersion value also allows the transmitted optical signal to have a greater bandwidth. There is also a flatted dispersion near zero over a larger frequency spectrum from 0.97 to 1.09 THz. In some cases, multiple optical signals with almost the same pulse spread can be transmitted simultaneously. The lower dispersion value also allows the transmitted optical signal to have a greater bandwidth. This type of behavior with optical parameters gives the proposed fiber a positive degree.

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

It has been found in Table 1, which shows better outputs compared to the former research work. We have found effective material loss of 0.0076 cm⁻¹, power fraction of 90%, confinement loss of $3.35 \times 10^{-16}$ cm⁻¹, and an effective area of $5.95 \times 10^{-8}$ m² at monitoring region of 1 THz.

### 3 Conclusion

A great plan of heptagonal cladding range with curved turned elliptical rotated-Hexa based core areas is presented for communication areas, reducing different types of losses such as effective material loss, confinement loss, and scattering loss. Using the heptagonal PCF concept, all graphical results have been accomplished with the FEM and PML boundary conditions based on the COMSOL Multiphysics test system. This designed PCF fiber uncovers a low effective material loss (EML) of 0.0076 cm⁻¹, with a larger effective area of $5.95 \times 10^{-8}$ m² and a core power fraction of 90% at 1 THz. In addition, the proposed H-PCF moreover has other user profiles like standard control due to EML (< 0.0076 cm⁻¹), low confinement loss ($\sim 3.35 \times 10^{-16}$ cm⁻¹), and high core power fraction ($\sim 90\%$). Thus, this anticipated H-PCF would be a favorable candidate within the telecommunication, IoT-based wireless sensor network, and other communication that is now under investigation.
| Reference                        | EML (cm$^{-1}$) | Porosity (%) | Power fraction | Confinement loss (cm$^{-1}$) | Effective area [$A_{\text{eff}}$ (m$^2$)] |
|---------------------------------|----------------|--------------|----------------|-------------------------------|------------------------------------------|
| Islam et al. (2015b)           | 0.100          | 30           | –              | $1.0 \times 10^{-01}$         | $2.3 \times 10^{-07}$                   |
| Hasan et al. (2016)            | 0.089          | 60           | 37%            | $1.0 \times 10^{-02}$         | $9.77 \times 10^{-08}$                  |
| Hasan et al. (2015)            | 0.076          | 80           | 53%            | $8.96 \times 10^{-01}$        | –                                        |
| Paul and Ahmed (2020b)         | 0.038          | 74           | 56%            | $2.35 \times 10^{-01}$        | $6.75 \times 10^{-05}$                  |
| Islam et al. (2016c)           | 0.110          | –            | –              | –                             | $0.98 \times 10^{-07}$                  |
| Paul et al. (2019)             | 0.027          | 85           | 83%            | $1.0 \times 10^{-02}$         | $9.48 \times 10^{-08}$                  |
| Ahmed et al. (2017)            | 0.068          | 50           | –              | –                             | –                                        |
| Rana et al. (2015)             | 0.050          | 60           | 42%            | 1.00                          | –                                        |
| Ahasan Habib and Shamim Anower (2018) | 0.07          | 30           | –              | $1.14 \times 10^{-3}$        | $1.07 \times 10^{-9}$                   |
| Sultana et al. (2018a)         | 0.05           | –            | 67%            | $7.79 \times 10^{-12}$        | $2.00 \times 10^{-5}$                   |
| Sultana et al. (2018b)         | 0.078          | 30           | –              | $1.39 \times 10^{-4}$        | –                                        |
| Islam et al. (2017c)           | 0.043          | 81           | 47%            | $1.00 \times 10^{-2}$        | $2.15 \times 10^{-5}$                   |
| Proposed H-PCF                 | 0.0076         | 74           | 90%            | $3.35 \times 10^{-16}$        | $5.95 \times 10^{-8}$                   |
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Declarations

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

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