

## RESEARCH ARTICLE

## Ultra-low loss and dispersion flattened microstructure fiber for terahertz applications

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## Abstract

In this paper, a rectangular core hexagonal lattice porous core photonic crystal fiber (PC-PCF) is reported for effectively guiding the terahertz light signal. Finite element method with circular perfectly matched layer boundary condition is employed to find out the propagation characteristics of this proposed porous core fiber. Extensive simulation results of that microstructure fiber over wide frequency range shows that very low effective material loss of  $0.035 \text{ cm}^{-1}$ , large effective area of  $1.79 \times 10^{-7} \text{ m}^2$  and high core power fraction of 36% can be obtained simultaneously. In addition, for same designing condition nearly zero flattened dispersion of  $0.46 \pm 0.07 \text{ ps/THz/cm}$  can be achieved over 600 GHz frequency band in terahertz range. Furthermore, other important parameters like single mode operation, confinement loss and bending loss are also investigated rigorously for the proposed fiber. The excellent results of this optical waveguide will pave the way to implement it in various real life terahertz applications.

*Keywords: Porous core PCF, Terahertz, Low absorption loss, Dispersion, Confinement loss.*

## 1. Introduction

Light is an electromagnetic signal and on the basis of frequency it is classified into various categories such as visible, infrared, ultraviolet etc. Among them, only a small band of light signal can be seen by the human eye (from 400 THz to 789 THz) and the other light signal cannot be distinguished by normal human eye [1]. However, many optoelectronics researchers have found a small frequency band of signal which can be implemented in various favorable applications in real life. This electromagnetic signal is named as terahertz radiation band which covers the frequency from 0.1 to 10 THz [2]. In the last few decades, this particular frequency signal is successfully implemented in various applications including chemical sensing [3, 4], communication [5], astronomy, imaging [6], and biotechnology [7] etc. Moreover, by using the terahertz signal now different cancer and tumor cells (breast tumor, skin cancer, colon tissue cancer etc.) are detected easily than other conventional medical process [8, 9]. According to the other communication scheme, terahertz communication system have major three parts and they are the terahertz generator, the channel and the terahertz receiver. The optoelectronics researchers have worked very hard to generate and to detect the terahertz signal and as a result the terahertz generator and detector are available in the market. Unfortunately, the proper channel to transmit the signal efficiently is not available in the market. The prime reason behind the failure is almost all proposed waveguides offered high absorption loss in that particular frequency range. So that, researchers are now proposing various types of low loss terahertz waveguides. It is known to all, the dry air shows non-absorbent characteristics in terahertz frequency range. That's why, porous core Photonic crystal fiber (PC-PCF) have become a new topic to the researchers rather than other waveguides such as metallic waveguide, parallel plate waveguide, two wire transmission line etc. In case of PC-PCF, the air holes are introduced in the both core and cladding region which offer two different functions. The air hole in

the cladding region provides the dielectric region around the core and the core air holes are used to reduce the solid material in the core so that the loss is reduced. Again, the effective material loss (EML) is also responsible to the types of background material and the commonly used background materials are Teflon [10], Topas [11], Zeonex [12], PMMA [13]. Previously stated that, the efficient terahertz waveguide is under research and that's why several remarkable designs of terahertz waveguides were proposed by the researchers which offered excellent guiding characteristics along with lower EML. A circular type PC-PCF was reported in [14] by Islam *et al.*, where core air holes are arranged in hexagonal manner. The simulation results showed that a very low EML of  $0.043 \text{ cm}^{-1}$  at 1 THz and ultra-flattened dispersion of  $0.09 \text{ ps/THz/cm}$  from 1-1.3 THz can be achieved at optimum condition. After that, in the year 2017, Hasan *et al.* reported a hybrid core microstructure fiber [15] which offered low bending loss of  $5.24 \times 10^{-13} \text{ cm}^{-1}$  at 1 THz and low dispersion of  $0.33 \text{ ps/THz/cm}$  over a wide frequency ranging from 0.9 to 1.6 THz. Nevertheless, the EML is  $0.08 \text{ cm}^{-1}$  at 1 THz which is slightly higher and will restrict the long distance communication. A single mode octagonal PC-PCF was proposed by Ahmed *et al.* which offered low EML of  $0.049 \text{ cm}^{-1}$  and high core power fraction of 54% at 1 THz [16]. Moreover, a rhombic shaped PC-PCF [17] was proposed by Hasan *et al.* which showed low dispersion of  $0.27 \text{ ps/THz/cm}$  at 1-1.4 THz and an EML of  $0.089 \text{ cm}^{-1}$  at 1 THz. After that, a rectangular core microstructure fiber was reported by Habib *et al.* in which simulation results confirmed that low EML of  $0.07 \text{ cm}^{-1}$  at 1 THz and almost zero flattened dispersion variation of  $0.02 \text{ ps/THz/cm}$  can be achieved at optimum designing parameter [18]. A PC-PCF was proposed by the same author of this manuscript in 2018, where a square type fiber offered low EML of  $0.06 \text{ cm}^{-1}$  as well as low confinement loss of  $9.2 \times 10^{-3} \text{ cm}^{-1}$  for a particular geometric condition [19].

In this paper, a PC-PCF is reported which shows very low absorption loss of  $0.035 \text{ cm}^{-1}$ , low confinement loss of  $6.3 \times 10^{-2} \text{ cm}^{-1}$ , high power

fraction of 36% at 1 THz at optimal geometric condition simultaneously. Furthermore, almost zero flattened dispersion variation of 0.07 ps/THz/cm can be achieved from 0.8 to 1.4 THz. The proposed fiber is very simple to realize because almost all the air holes are circular shaped which can be fabricated with less complexity. We hope this proposed fiber can be easily fabricated by using the sol-gel technique and it will be a strong candidate in different real life terahertz applications.

## 2. Modelling of proposed PC-PCF

The two dimensional cross-sectional view of the presented PC-PCF is shown in Figure 1. In this optical waveguide, hexagonal type structure is selected for the cladding section due to its superior characteristics (compact, easy to fabricate, better light confinement *etc.*) than other structures. The diameter of all cladding air holes are equal and symbolized by  $d$  ( $d=0.95 \times \Lambda$ ) and it was fixed throughout the total simulation work where  $\Lambda$  (pitch) stands for the distance between two adjacent air holes in same ring and two adjacent rings. Here, 0.95 is the air filling fraction which is the ratio between the area occupied by the air holes and total fiber fiber dimension. In order to create rectangular core two cladding air holes are converted into two half circles. For simplicity, the length and width of the rectangular core are also related to  $\Lambda$  which are denoted by  $L_{core}$  and  $W_{core}$  respectively, where  $L_{core}=3 \times \Lambda$  and  $W_{core}=2.5 \times \Lambda$ . Total 20 circular air holes are introduced in four rows in the core region. The distance between two air holes in two adjacent columns is symbolized by  $l_c=0.5 \times \Lambda$  and for two adjacent column it is  $l_r=0.5 \times \Lambda$ . A circular perfectly matched layer (PML) is used to extract the wave propagating towards the surface to eliminate the back reflection whose thickness is 10% of the total fiber diameter. Different types of polymer are used as the background material for THz waveguide, among them TOPAS is selected as the base material for that fiber. The reasons behind that are the refractive index of TOPAS is 1.5258 which remain constant in 0.1-2 THz range and the bulk absorption loss is  $0.2 \text{ cm}^{-1}$  in THz regime [18].

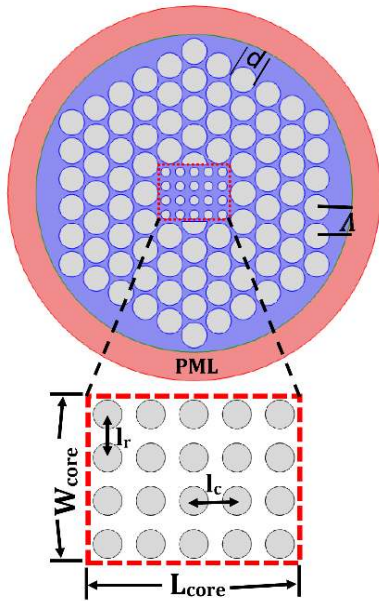


Figure 1. Cross-sectional view of the proposed PC-PCF.

## 3. Numerical analysis and discussions

To realize the effectiveness of the proposed PC-PCF, the propagation characteristics are found out by employing commercially available software named Comsol Multiphysics V4.2 which uses Finite Element Method (FEM) to solve the required mathematical equations. In order to ensure better accuracy, extremely fine mesh element is utilized which is shown in Figure 2. During the simulation procedure the following numerical values are provided by the previously stated software: total mesh elements= 51711, total boundary elements=5419 and vertex elements= 432.

Mainly, three types of major losses occurs in any kind of PC-PCF which are known as the effective material loss, the confinement loss and the bending loss. Effective material loss (EML) is also known as absorption loss, bulk material loss, effective mode loss *etc.* which happens due to the absorption of light energy by the solid background material. EML is a key parameter for any PC-PCFs as it limits the long distance communication. This loss can be easily quantified by using the following equation [18],

$$\alpha_{eff} = \frac{\left(\frac{\epsilon_0}{\mu_0}\right)^{1/2} \int_{A_{mat}} n \alpha_{mat} |E|^2 dA}{2 \int_{All} S_z dA} \quad (1)$$

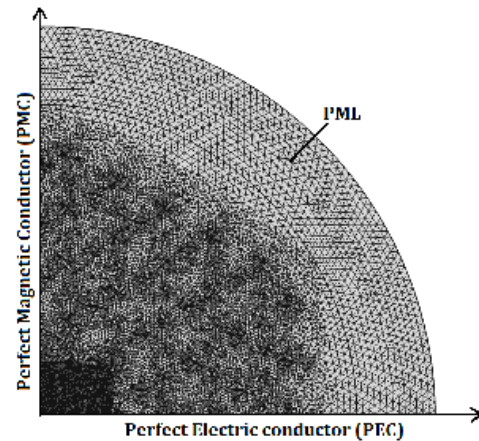


Figure 2. Extremely fine mesh element of the proposed PC-PCF.

where  $n$ ,  $\epsilon_0$ , and  $\mu_0$  are the effective refractive index of bulk material, relative permittivity of air and relative permeability of free space, respectively. Again, the bulk material loss is presented by  $\alpha_{mat}$ ,  $E$  represents the electric field component, and  $S_z$  is the z-component of the Poynting vector. The numerator and denominator of the above equation performs the integration of Topas and the total fiber respectively. EML is mainly dependent on the amount of solid material present in the fiber. Hence, maximum EML occurs when the core is solid and the EML reduces with the introduction of air holes in the core region. EML at 1 THz as a function of  $L_{core}$  for different core

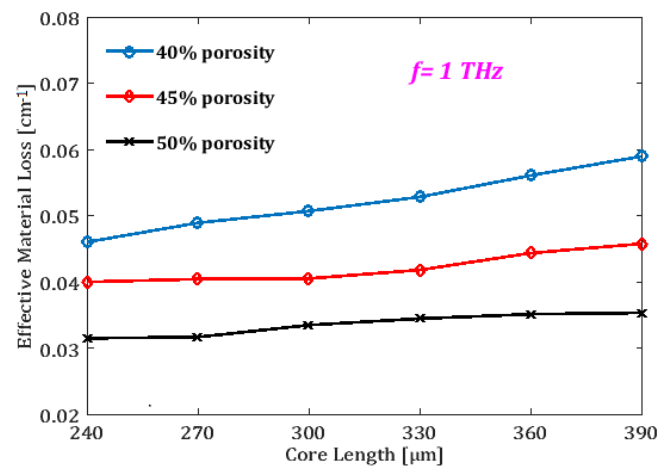


Figure 3. Effective material loss of the proposed fiber as a function of core length.

porosities is represented in Figure 3 where it is clear that, EML is very low ( $0.032 \text{ cm}^{-1}$ ) at 50% porosity and  $240 \mu\text{m}$  of  $L_{core}$ . Anyway, due to lower power fraction through air core  $L_{core}=240 \mu\text{m}$  cannot be considered as optimum core length which will be discussed in the further section. In the meantime, the EML of the proposed fiber is  $0.035 \text{ cm}^{-1}$  for 50% core porosity at  $L_{core}=390 \mu\text{m}$ , which informs that the bulk material loss in the core reduced by 82.5%. Moreover,

Figure 3 clearly indicates that, for a particular core length the bulk absorption loss reduces with the increase of core porosities. This is due to the fact that less material is experienced in the core for higher porosity and hence most of the power resides in the air holes in the core. For instant, at 1 THz and  $L_{core}=390\ \mu\text{m}$  the EML are  $0.059\ \text{cm}^{-1}$ ,  $0.045\ \text{cm}^{-1}$  and  $0.035\ \text{cm}^{-1}$  for 40%, 45% and 50% core porosities, respectively. Now, the EML of the proposed rectangular core fiber for different operating frequencies is reported in Figure 4. We all know that the higher frequency signal always try to travel through higher refractive indexed zone. At higher frequency more light propagates through the core region and trapped by the solid material as a result the EML increases with the increase of frequency at a particular geometric condition. From Figure 3 and Figure 4 we can say that, the obtained EML at 50% core porosity is better than the ones previously reported in Ref. [14-19].

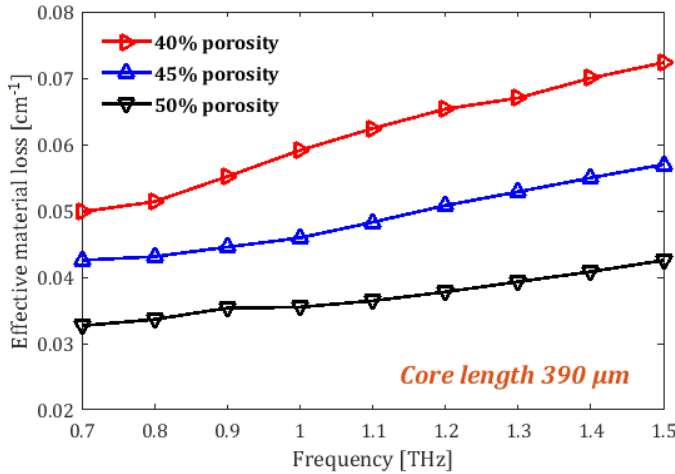


Figure 4. EML as a function of frequency for different core porosities.

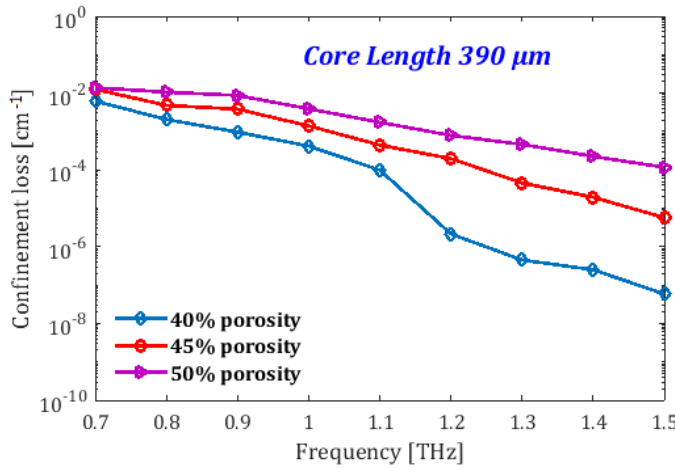


Figure 5. Confinement loss of the proposed fiber for different operating frequencies.

In case of all types of optical waveguide, there exist another kind of loss and it is called confinement loss. When the light wave travels through the core, then some amount of light came out from the core and trapped by the cladding air holes. This type of loss is indicated by confinement loss and it can be calculated by using the following expression [18],

$$\alpha_{CL} = 8.686 \times \frac{2\pi f}{c} \text{Im}(n_{eff}) \quad (2)$$

where,  $\text{Im}(n_{eff})$  symbolizes the imaginary part of the refractive index,  $f$  is the frequency of the light wave and  $c$  is the velocity of light in free space. Figure 6 shows the calculated confinement loss for different operating frequencies and porosities when core length is  $390\ \mu\text{m}$ . The graphical representation informs that at a fixed frequency  $\alpha_{CL}$  decreases with the decrease of core porosity. This happens because

the refractive index difference between core and cladding is increased by the decrease of core porosity which helps to confine the light better in core region. It is beneficial to note that at  $f \approx 1\ \text{THz}$  and 40% porosity, a structure with  $L_{core}=390\ \mu\text{m}$  offers a confinement loss of  $6.3 \times 10^{-3}\ \text{cm}^{-1}$  which is comparable with the previous works in [14-19].

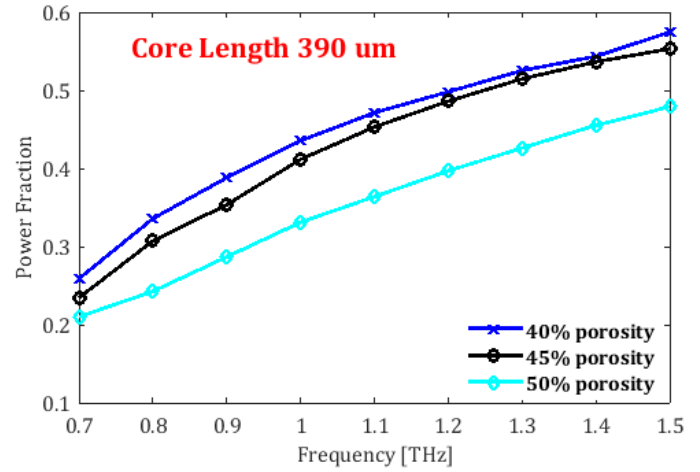


Fig. 6. Power fraction through the core of the proposed PCF for different frequency.

In both communication and sensing applications, it is desired that maximum amount of energy will propagate through the core region. The fraction of total transmitted power travels through the core air hole known as power fraction and it is an important parameter. For low loss and long distance transmission, the power fraction should be as high as possible. How much power is carried out through the core air holes can be calculated by using the following expression [16],

$$\eta = \frac{\int S_z dA}{\int_{All} S_z dA} \quad (3)$$

where,  $\eta$  represents mode power fraction and  $X$  represents the area covered by core air holes. Fig. 6 shows the power fraction through the core of that proposed porous core fiber for different operating frequencies at  $L_{core}=390\ \mu\text{m}$ . From the following figure it is clear that the power through the core air hole increases with the increase of operating frequency and decrease of core porosity. This happens because additional higher frequency light propagates through the core than lower frequency's and the higher core porosity reduce the core-cladding refractive index difference and the light try to come out from the core. It is worthwhile to note that, at 1 THz for 45% and 50% core porosity almost 43% and 36% power propagates through the core when  $L_{core}=390\ \mu\text{m}$ , respectively.

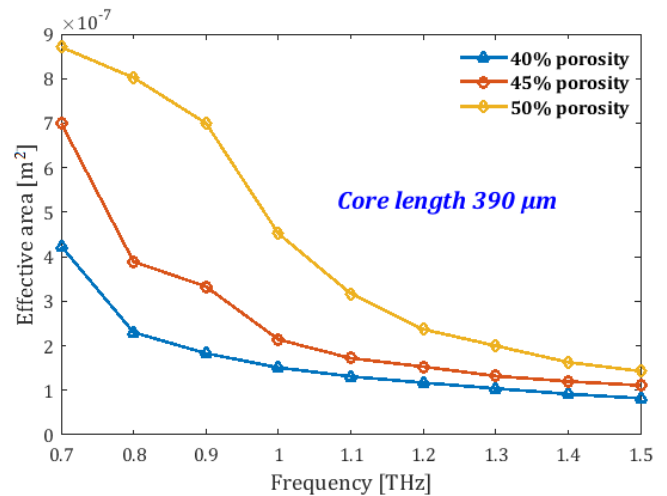


Figure 7. Effective area of the proposed fiber as a function of frequency.

Effective area is another guiding property of efficient THz waveguide which provides the information about the actual fiber area through which the light signal transmitted. The desired level of effective area is application dependent and both larger (e.g. Laser source, THz communication devices etc.) and smaller (e.g. optical fiber communication etc.) area PC-PCFs have been reported by the researchers. This area can be easily quantified by using the following equation [18],

$$A_{eff} = \frac{\left[ \int I(r) r dr \right]^2}{\left[ \int I^2(r) dr \right]^2} \quad (4)$$

where,  $I(r) = |E_t|^2$  is the electric field of the fundamental guided mode. The effective area of the proposed single mode fiber at optimal core length is reported in Fig. 8. From that graphical representation we can see that, the effective area is in the order of  $1.79 \times 10^{-7} \text{ m}^2$  for  $L_{core}=390 \mu\text{m}$  and 50% porosity which is better than reported works in literature [14-19].

Now, V parameter is analysed for the proposed rectangular core PCF to ensure single mode fashion guidance. If the numerical value of this parameter is less than or equal to 2.405 then the fiber is called single mode fiber. In case of multimode fiber, there will be interaction of two different guided modes and it is called as intermodal distortion. For efficient transmission of signal the proposed fiber should be single mode fiber. This parameter can be easily calculated by using the following expression [16],

$$V_{eff} = \frac{2\pi f r}{c} \sqrt{n_{co}^2 - n_{cl}^2} \quad (5)$$

where,  $r$  is half of the core length,  $f$  is the operating frequency,  $c$  is the velocity of light in free space,  $n_{co}$  and  $n_{cl}$  are the effective refractive index of core and cladding, respectively. As the air filling fraction of cladding is very high (almost 0.95) so the refractive index of the core is taken 1.02 throughout the whole calculation. Fig. 8 exhibits the V parameter of the proposed fiber for different operating frequency when  $L_{core}= 390 \mu\text{m}$ . The following figure shows that the fiber will operate as single mode fiber for 0.7-1.5 THz when core porosity is 50% and for 0.7-1.35 THz when 45% porosity is used.

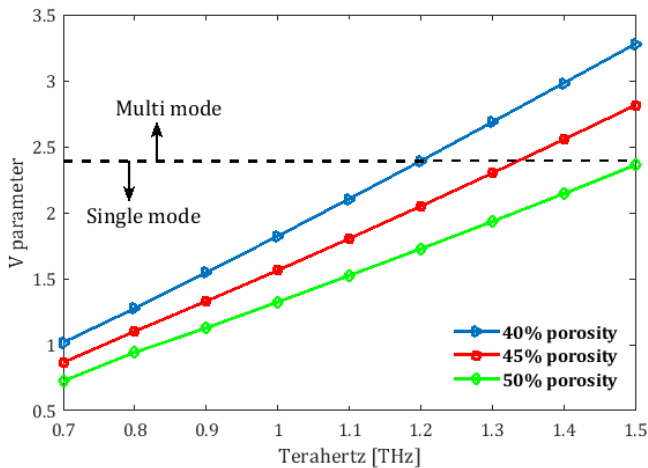


Figure 8. V parameter of the proposed PCF for different operating frequencies at optimum core length.

Now, the last loss mechanism of a PC-PCF will be investigated which is called bending loss. The loss is negligible in case of straight fiber and this type of loss is present inside of the fiber when it is bent. At bending region some light energy came out from the core and absent at the receiving end. Bending loss can be calculated by using the following equation [18],

$$\alpha_{BL} = \frac{1}{8} \sqrt{\frac{2\pi}{3}} \frac{1}{A_{eff}} \frac{1}{\beta} F \left[ \frac{2}{3} R \frac{(\beta^2 - \beta_{cl}^2)^{3/2}}{\beta^2} \right] \quad (6)$$

where,  $R$  is the bending radius,  $F(x) = x^{-1/2} e^{-x}$ , the propagation constant  $\beta$  and  $\beta_{cl}$  are defined as  $\beta = 2\pi n_{co} / \lambda$  and  $\beta_{cl} = 2\pi n_{cl} / \lambda$  respectively and  $A_{eff}$  is the effective area of guided mode light. Bending loss of the proposed fiber for optimal core length as a function of frequency is shown in Fig. 9. As the light gets better confinement through the core at high frequency, so that the bending loss reduces with the increase of operating frequency at a particular geometric condition. At 1 THz the bending loss is  $1.03 \times 10^{-7} \text{ dB/m}$  and which is comparable with the previous reported works in literature [14-19].

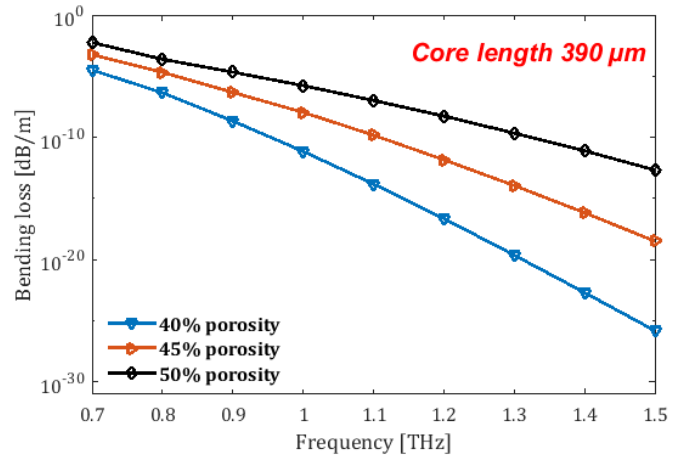


Figure 9. Bending loss of the proposed fiber as a function of frequency for  $R= 1\text{cm}$ .

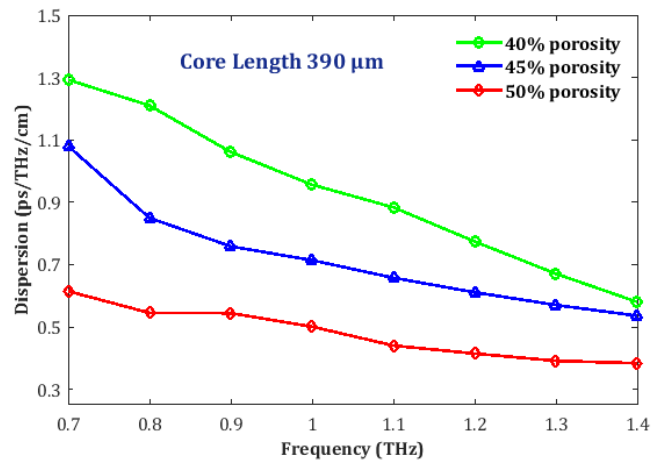


Figure 10. Dispersion characteristics of the proposed fiber at optimum core length.

Finally, the dispersion characteristics of the proposed fiber will be analysed. In optical waveguide, mainly two types of dispersion occurs and they are called waveguide dispersion and material dispersion. The first one is dependent on the geometry of the fiber and the last one is dependent on the bulk material. The material dispersion is neglected here because the refractive index of the base material remain constant over the frequency range 0.1-2 THz. That's why only the waveguide dispersion is discussed here. The dispersion of any porous core PCF can be easily calculated by using the following expression [18],

$$\beta_2 = \frac{1}{c} \left( 2 \frac{dn}{d\omega} + \omega \frac{d^2n}{d\omega^2} \right) \quad (7)$$

where  $\omega = 2\pi f$ ,  $f$  is the frequency of the light wave,  $c$  is the velocity of light in vacuum and  $n$  is for the effective refractive index of the guided mode. The dispersion variation of the proposed fiber is shown in Fig. 10 for different core porosities as a function of frequency. It is worthwhile to note that our proposed fiber exhibits almost zero flattened dispersion of  $0.46 \pm 0.07$  ps/THz/cm over a wide frequency range from 0.8 to 1.4 THz for optimum core length.

At last we will discuss about the possible fabrication methodologies of that proposed fiber. Except two cladding air holes all the air holes of our proposed fiber are circular in shape. Fabrication of circular air holes are very easy and can be fabricated with great accuracy by using the available methods. So, this fiber can be easily fabricated by using ongoing fabrication technology such as extrusion, drilling and stack, sol gel technique etc. We propose extrusion technique [18] to fabricate that proposed fiber because by using this technique one can easily fabricate that.

#### 4. Conclusions

We propose a rectangular type porous core PCF is proposed for the efficient transmission of terahertz signal. Hexagonal type lattice is used in the cladding region for better confinement of light and rectangular core is used to introduce maximum air holes. The simulation results confirm that this porous fiber offers ultra-low effective absorption loss of  $0.035 \text{ cm}^{-1}$  for optimum designing parameter at 1 THz. Moreover, very low dispersion variation of 0.07 ps/THz/cm can be achieved over a wide bandwidth of 600 GHz. Along with the low EML and pulse spreading, the proposed fiber also provides very high power fraction and low confinement loss and bending loss. As low loss optical waveguides have various promising applications in different sectors such as telecommunication, biomedical imaging, spectroscopic and sensing applications etc. This fiber can be easily fabricated with the modern ongoing technology as the introduced air holes are circular in nature. So that we hope this PC-PCF will be a good candidate in terahertz applications.

#### Nomenclature

PC-PCF: Porous core photonic crystal fiber

THz: Terahertz

EML: Effective material loss

PMMA: Poly methyl methacrylate

#### Declaration of Conflict of Interests

The author declare that there is no conflict of interest.

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