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Low loss topas based porous core single mode photonic crystal fiber for THz communications

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In this paper, an extremely low loss hybrid hexagonal porous core and octagonally structured circular cladding photonic crystal fiber (PCF) for low loss terahertz (THz) wave propagation has been designed and proposed. We have analyzed ultralow effective material loss (EML), high core power fraction and ultra-flattened dispersion in our proposed design. To investigate the transmission characteristics, perfectly matched layer (PML) is used in the outer boundary of the PCF. At an operating frequency of 1 THz, this design exhibits a low effective material loss of $0.045\ cm^{-1}$ at a high core power fraction of 58.2 % with 88 % porosity. The proposed PCF shows dispersion variation of 0.225 ps/THz/cm. Also, this designed PCF can operate in single-mode condition successfully. It is anticipated that designed PCF can be employed in applications such as fiber optics communications, sensing and spectroscopy.

Keywords: Terahertz, Porous-core, Effective material loss, Power fraction, Confinement loss, Dispersion

1 Introduction

Electromagnetic wave lying between millimeter wave and infrared ray in the frequency range of 0.1 THz to 10 THz has attracted the researchers for their wide spread applications in communications[1], biosensing[2], spectroscopy[3] and imaging[4]. Properties like wide-range, single-mode operation, low loss and highly sensitive photonic crystal fibers widely known as PCFs have been the topic of research in recent times. This is because, PCFs offers immense geometric design flexibility over the conventional fibers. In PCFs, we can efficiently control wave guiding properties, such as mode properties, EML, dispersion and mode confinement through tuning of parameters of air holes[5].

Metallic wires[6] and metal-coated dielectric tube[7] were used in the early stages of this ever continuous research. But soon these waveguides became obsolete as they suffered from bending loss, low coupling efficiency and unbalanced guidance in complex atmosphere during transmission[8,9]. Thus waveguide were modified to less lossy plastic sub wavelength fibers[10]. But it caused strong coupling to the environment, as most of the field propagated outside the waveguide. For further modifications[11], they proposed a fiber which contains a hole inside the solid core. Although, the presence of this air hole reduced the absorption loss but the material loss remained high. As it is mainly depends on the properties of background materials, it is possible to reduce the material absorption loss by increasing the core power fraction and maintaining tight confinement inside the air holes of the core.

Polymer materials like PMMA[12], Teflon[13] and Topas[14] are good as background material for designing THz PCF. Among them topas exhibits lower absorption loss compare to other. In the view of further reduction of absorption loss, polystyrene foam[15] and hollow core brag fibers[16] were used. But the technology could not sustain as it showed the narrow band properties as well as having physical strength issue. With the aim of improving field confinement and EML reduction, researchers have proposed topas based porous core photonic crystal fiber for THz communication.

Photonic crystal fiber is a micro-structured optical waveguide with finite number of air holes in the core and cladding[17-19]. In literature[20], they have proposed an octagonal core shaped optical fiber with Topas as the background material. The porous core design reported a reduced material loss of 0.076 cm^{-1}. But they neglected to analyze core power fraction. Later, in literature[21] proposed a fiber hexagonal core and rotate hexagonal cladding and showed EML of 0.066 cm^{-1} and power fraction of 40% yet the EML remained high. Later, in literature[22] they proposed a

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fiber with decagonal core and cladding with EML of 0.058 cm^{-1} but they neglected to investigate dispersion properties of the fiber. In literature[23], they have proposed a fiber with circular cladding and rotate hexagonal core. They obtained competitive value of EML 0.053 cm^{-1} at the power fraction of 47%.

In this paper, hybrid hexagonal core surrounded by five layered octagonal structured cladding has been proposed. Important properties like effective material loss, single mode propagation, core power fraction, dispersion, confinement loss and power in the air holes has been discussed in details. At the power fraction of 58.2% and frequency of 1 THz the proposed fiber exhibits lower material loss of 0.045 cm^{-1} which is much lower than the previously proposed fibers.

2 Methodology

The cross section of the proposed design is shown in Fig. 1. The air holes of the core and cladding of the proposed fiber are arranged in octagonal and hybrid hexagonal structure respectively which accumulated 49 air holes with different radii.

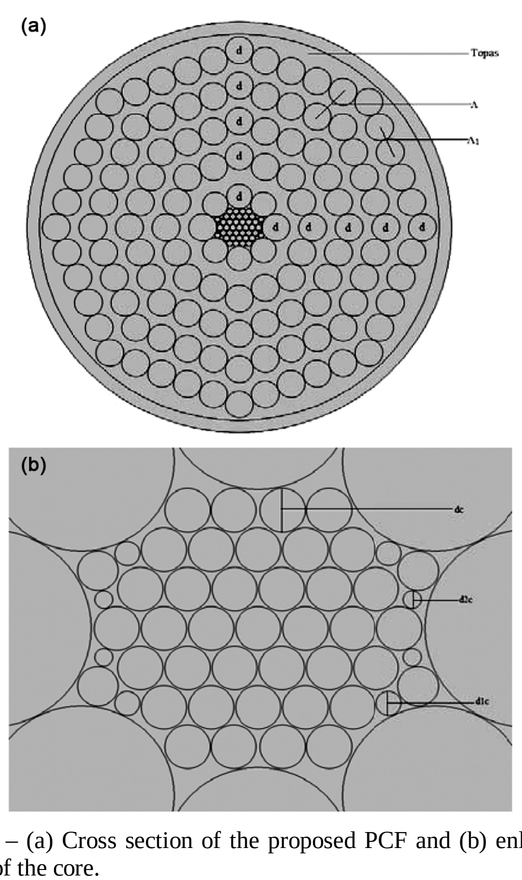

Fig. 1 – (a) Cross section of the proposed PCF and (b) enlarged view of the core.

Octagonally designed cladding has facilitated the model with 1.32 times more air holes in the cladding in compare to a hexagonal structure with the same number of layers. 5 rings of air holes in the cladding have increased the confinement properties decreasing the material absorption loss. Since, air holes in the core operate as low index and dry air is transparent in THz frequency band. With the increase in number of air holes in the core, effective material loss decreases. Thus, hybrid hexagonal core has been considered as it has accumulated 49 air holes in the core will be able to reduce EML.

In cladding, the distance between the air holes on two adjacent rings is denoted by Λ and the distance between two adjacent air holes in the same ring is denoted by Λ_1. The relation between them is expressed by Λ_1=0.76Λ. The air filling fraction (AFF) is usually represented by d/Λ where d represents the diameter of the air holes. The value was fixed at 0.75 throughout the whole numerical analysis. As higher air filling fraction (AFF) increases the core confinement reducing the effective material loss (EML), AFF has been kept constant. AFF in the core diameter $D_{core}=2(\Lambda-d/2)$ is variable and is mostly determined by the core porosity which is defined as the ratio of the air hole area to the cross section area of the core. Throughout the analytical process porosity, frequency and core diameter have been varied with a keen consideration to single mode condition. In the design 41 air holes are of the diameter d_c, 4 air holes of diameter $d1_c$ and 4 air holes of diameter $d2_c$ have been accumulated to provide a multi radii hybrid hexagonal complex porous core. During simulation the relation between $d1_c$ is considered to be 0.55 times of d_c and the diameter $d2_c$ has been reduced to 0.4 times of d_c. The diameter of the cladding air holes is 4.57 times of d_c.

Cyclic-olefin copolymer, TOPAS has been as the background material because of its certain properties like: (i) lower material absorption loss which is about 0.2 cm^{-1} at f=1 THz, (ii) constant refractive index[24] n=1.53 in the range of 0.1-1.5 THz, (iii) it is not an absorber water vapor[25], (iv) it is ultra-violet photosensitive and good for bio sensing and (v) different grades can make it to obtain high glass transition temperature. Besides, the material absorption loss of TOPAS is much less in compare to Teflon or PMMA. This particular refractive index has resulted to almost zero dispersion.

3 Simulations and Results

The key propagating properties of the proposed PCF were evaluated using COMSOL multi-physics version 4.3 b. A circular perfectly matched layer (PML) has been considered. The layer is about 9 % of the total radius of the whole fiber and has been used outside the computation domain for obtaining accuracy in the calculation of leakage loss. The power flow distribution provided in Fig. 2 with the core porosity of 88 % establishes the fact that light is well confined inside the core.

It is advised to ensure that the single mode condition of the proposed fiber is not hampered with the modification of core diameter and frequency. Single mode properties were carefully analyzed focusing on this idea. Normalized frequency or V-parameter can be calculated[26] by:

$$V = \frac{2\pi r f}{c}\sqrt{{n_{co}}^2 - {n_{cl}}^2} \leq 2.405 \qquad \ldots (1)$$

Where, r is defined as the core radius, c is the speed of light in vacuum, n_{co} and n_{cl} are the refractive indices of core and cladding, respectively. Single mode condition is ensured when the normalized frequency V is equal to or less than 2.405. The refractive index of air[27] is 1 thus, it is advantageous in assuming n_{cl}=1 as the cladding consists of numerous numbers of air holes. The core refractive index n_{co} is considered to be effective refractive index (n_{eff}) because of the porous core.

Figure 3 and 4 shows the variation of normalized frequency V with respect to different values of core diameter and frequency f. From Fig. 3 and 4 we can see that V parameter increases with the increase of both core diameter and frequency.

For designing an efficient THz waveguide, two loss properties must be considered. They are effective material loss and confinement loss. The aim of the researchers from the preliminary stage was to reduce the effective material loss significantly. The effective material loss especially for PCF is often calculated[28] by:

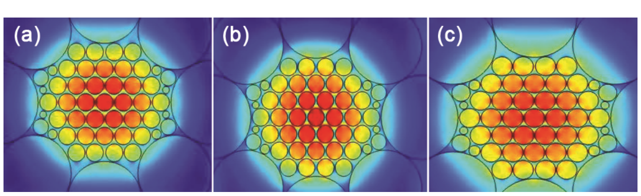

Fig. 2 – (a) Power flow distribution of the proposed PCF at 71% porosity., (b) Power flow distribution of the proposed PCF at 81% porosity., (c) Power flow distribution of the proposed PCF at 88% porosity.

$$\alpha_{eff} = \sqrt{\frac{\varepsilon_0}{\mu_0}}\left(\frac{\int_{mat} n_{mat}|E|^2\alpha_{mat}\, dA}{2\left|\int_{all} S_z\, dA\right|}\right) \qquad \ldots (2)$$

Where, ε_0 and μ_0 are the relative permittivity and permeability in vacuum, respectively. α_{mat} represents the bulk material absorption loss, n_{mat} is defined as the refractive index of Topas, E is the modal electric field and S_z is the z component of the pointing vector (S_z = ½(E × H).z). Here E and H are the electric and magnetic fields, respectively.

When the porosity decreases the EML also decreases as the core material decreases. Figure 5 highlights the facts that, for the same porosity values there is a significant change of EML found when the core diameter varies. Considering all these factors, EML of 0.045 cm^{-1} at core diameter of 324 µm and frequency of 1 THz is found to be the most minimized value.

Confinement loss is an important parameter to be considered in PCF designing. It depends upon the core porosity and the number of air holes used in cladding. It is calculated considering the imaginary part of the complex refractive index and it follows the given equation[29]:

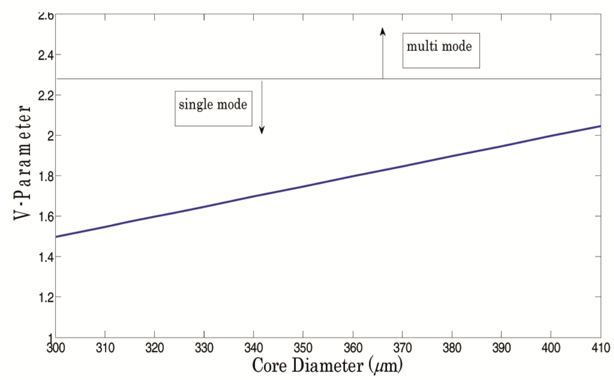

Fig. 3 – V parameter versus core diameter with f=1THz and porosity=88%.

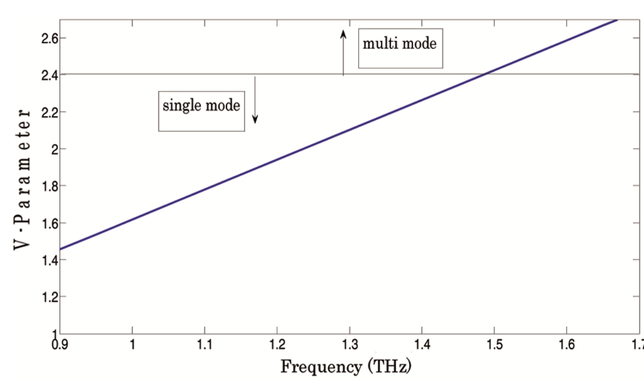

Fig. 4 – V parameter versus frequency at D_{core}=324µm and porosity=88%.

$$L_C = 8.686 \left(\frac{2\pi f}{c}\right) \mathrm{Im}(n_{eff}) \left(\mathrm{dB}/\mathrm{cm}\right) \quad \text{... (3)}$$

Where, f is the frequency of the guiding light, *c* is speed of light in vacuum and Im (n_{eff}) symbolizes the imaginary part of the refractive index.

The confinement loss as a function of frequency is shown in Fig. 6. The figure justifies that confinement loss reduces with the rise in the frequency. In the designed fiber, at f =1 THz, D_{core}= 324 μm and at 88% porosity, a low confinement loss of $10^{-1.5}$ cm^{-1} is found.

The parameter which has been well explained in the paper that is the amount of mode power propagation throughout the core air holes. To meet the criteria of standard PCF maximum power must pass through the core. The mode of power propagating through different regions of the fiber also known as core power fraction can be calculated[30] by:

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

Where, η' represents mode power fraction (PF) and X represents the area covered by air holes.

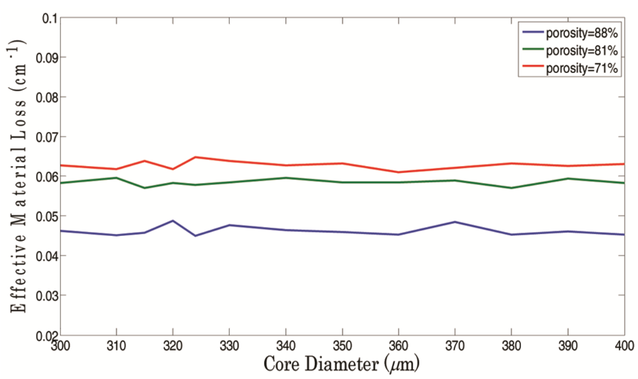

Fig. 5 – Effective material loss as a function of core diameter at different porosities with f=1 THz.

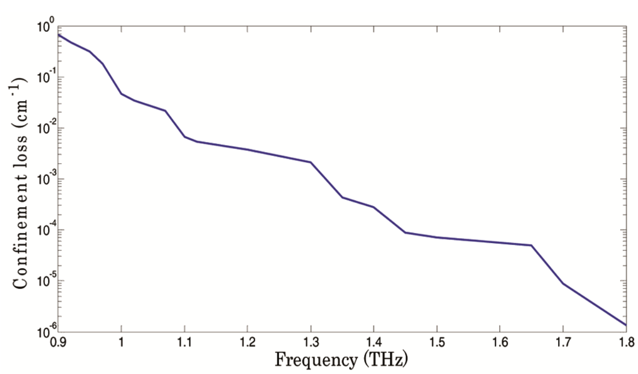

Fig. 6 – Confinement loss as a function of frequency variation at D_{core}=324 μm and porosity=88%.

In Fig. 7 effective material loss at different frequencies has been expressed. From the observation it can be illustrated that as the frequency increases the effective material loss also increases. Here, we have observed the range of frequencies between 0.9 and 1.8 THz as it is the single mode region. By observing the EML versus frequency, it has been found that the bulk material absorption loss of topas is not constant over the frequency range of 0.9-1.8 THz and it increases linearly with the frequency. From Fig. 7 and Fig. 8 it can be interpreted that at 88% core porosity and D_{core}=324 μm at 1 THz frequency, the EML is minimum which is 0.045 $cm^{-1}$and the total power in the air core is 58.2% which is sufficient for THz wave guidance as compared in Table 1.

Now, dispersion characteristics of our proposed PCF are discussed. The refractive index of TOPAS is constant over the frequency range 0.1-1.8 THz[31]; so its material dispersion can be neglected in this band. That is why waveguide dispersion is analyzed in this case. Dispersion parameter can be calculated by using the following equation[32]:

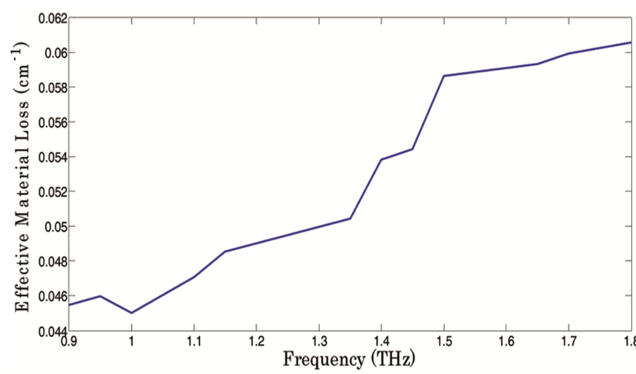

Fig. 7 – Variation of EML with respect to frequency at D_{core}=324 μm and porosity=88%.

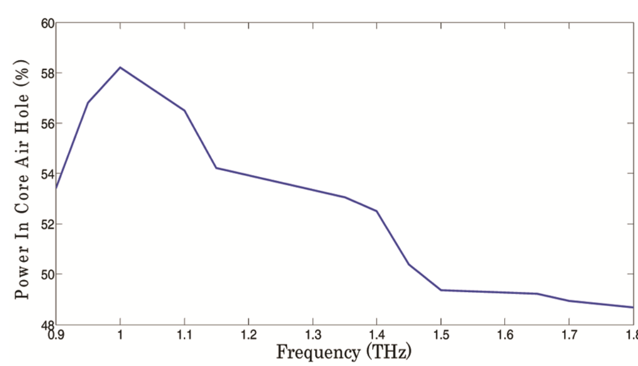

Fig. 8 – Power fraction as a function of frequency at D_{core}=324 μm and porosity=88%.

Table 1 – Comparison between EML and core power fraction with other design.

Ref.	EML (cm^{-1})	*Power fraction (%)*
[30]	0.085	~ 43.10
[31]	0.070	Not mentioned
[32]	0.14	~ 58.0%
[36]	0.066	~46.2%
Present work	0.045	58.2%

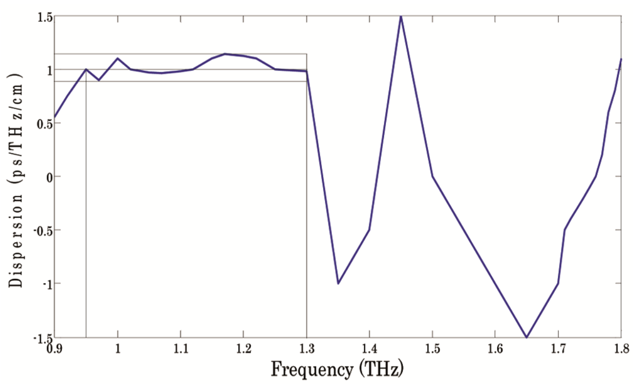

Fig. 9 – Frequency dependent dispersion at D_{core}=324 μm and porosity=88%.

$$\beta_2 = \frac{2}{c}\frac{dn_{eff}}{d\omega} + \frac{\omega}{c}\frac{d^2 n_{eff}}{d\omega^2} \quad \dots (5)$$

Where, ω=$2\pi f$ and c is the velocity of light in vacuum.

Dispersion characteristics are shown in Fig. 9 where we can see that the flatness of dispersion is achieved within the frequency range of 0.95 to 1.3 THz which is comparable to the report in literature[15]. Here, we can also see $\beta_2 < 1.25$ ps/THz/cm and $\beta_2 > 0.8$ ps/THz/cm. So, the variation of dispersion is less than 0.225 ps/THz/cm. In THz waveguide, dimension of β_2 is ps/THz/cm which indicates how much signal broadens in time (ps) per unit bandwidth (THz) for a propagation distance of 1 cm. In waveguides flat dispersion is highly expected as it allows transmitting several optical signals at the same time with nearly equal pulse spreading.

Table 1 provides a comparison between the designed fiber and others porous core structures reported in the literature for THz wave guidance. It can be observed that the proposed PCF has the highest core power fraction as well as lower effective material loss.

4 Fabrication Methods

Fabrication is an important issue for the practical realization of the fiber[5]. To date, a number of ongoing fabrication methods such as extrusion, capillary stacking, stack and drilling are applied to fabricate a wide variety of fiber performs and structures. High porosity both in the core and in the cladding, increases the fabrication difficulties of the PCF; however, technologies used for microstructure fibers have made it easy to some extent. However, difficulties arise during the fabrication of noncircular holes in microstructure fibers due to a lot of reasons, which include the action of surface tension, viscous stresses, heating and pressure effects during the fiber draw. If the shape of the air holes is not circular[33] in the preform stage, those effects subsequently lead to non-uniformly oriented whole deformations[34]. As our proposed fiber consists only of circular air holes, both in the core and in the cladding, it is expected that the fabrication of the fiber will be achieved using the stack and draw technique[35].

5 Conclusions

A comparatively simpler TOPAS based PCF with ultra-low material loss of 0.045 $\mathbf{cm^{-1}}$, higher core power fraction of 58.2% has been proposed in this paper. The proposed PCF is superior to the previously proposed PCF because of its lower EML, higher core power fraction properties and simplicity in design. Therefore, if the proposed fiber is utilized properly it can be an asset for efficient, long distance and flexible transmission of THz signals because of its ultra-low material loss and higher power fraction properties.

References

1 Islam R, *Opt Fiber Technol*, 24 (2015) 38.
2 Wang X D & Wolfbies O S, *Anal Chem*, 88 (2016) 203.
3 Fischer B M, Helm H & Jepsen P U, *Proc IEEE*, 95 (2007) 1592.
4 Awad M M & Cheville R A, *Appl Phys Lett*, 86 (2005) 221107.
5 Rana S, Nirmala K & Harish S, *Photonics*, 40 (2018) 1.
6 Bowden B, Harrington J & A Mitrofanov, *Opt Lett*, 32 (2007) 2945.
7 Ghasemi A H & Latifi H, *Opt Lett*, 37 (2012) 2727.
8 Nielsen K, Henrik K R, Adam A J L, Paul C M, Bang O & Jepsen P U, *Opt Exp*, 17 (2009) 8592.
9 Skorobogatiy M & Dupuis A, *Appl Phys Lett*, 90 (2007) 113514.
10 Atakaramians S, Afshar S, Fischer B M, Derek A & Tanya M M, *Opt Exp*, 16 (2008) 8845.
11 Chen L J, Chen H W, Kao T, Lu J & Sun C, *Opt Lett*, 31 (2006) 308.
12 Zhao G, Mors M, Wenckebach T & Planken P C M, *J Opt Soc Am B*, 19 (2002) 1476.
13 Lu J, Yu C P, Chang H C, Chen H W & Li Y T, *Appl Phys Lett*, 92 (2008) 064105.

14 Hameed M F O, Heikal A M, Younis B M, Abdelrazzak M & Obayya S S A, *IEEE Photon J*, 1 (2009) 265.
15 Hameed M F O & Obayya S S A, *IEEE J Lightwave Technol*, 30 (2012) 96.
16 Kaijage S F, Ouyang Z & Jim X, *IEEE Photon Technol Lett*, 25 (2013) 1454.
17 Rana S, Hasanuzzaman G K M, Habib S, Kaijage S F & Islam R, *Opt Eng*, 53 (2014) 115.
18 Hasan M I, Razzak S M A, Hasanuzzaman G K M & Habib M S, *IEEE Photon Technol Lett*, 26 (2014) 23.
19 Islam R & Rana S, *Opt Eng*, 54 (2015) 95.
20 Yoshinori K, Hiroki N & Yasunori, *IEICE Trans Electron*, 89 (2006) 830.
21 Emiliyanov G, Jensen J B, Bang O & Hoiby P E, *Opt Lett*, 32 (2007) 460.
22 Nielsen K, Rasmussen H K, Jepsen P U & Bang O, *Opt Lett*, 36 (2011) 666.
23 Snyder A W, *Optical Waveguide Theory*, (Chapman & Hall: London, UK), 1983.
24 Bao H, Nielsen K, Rasmussen H K & Jepsen P U, *Opt Express*, 20 (2012) 29507.
25 Chen N, Liang J & Ren L, *Appl Opt*, 52 (2013) 5297.
26 Liang J, Ren L, Chen N & Zhou C, *Opt Commun*, 295 (2013) 257.
27 Hasan M I, Habib M S & Razzak S M A, *Opt Fiber Technol*, 20 (2014) 32.
28 Roze M, Ung B, Mazhorova A & Walther M, *Opt Exp*, 19 (2011) 9127.
29 Hasan M I & Habib M S, *Photon Nanostruct Fundam Appl*, 12 (2014) 205.
30 Bise R T & Trevor D J, *Opt Fiber Commun Conf*, 2005.
31 Hasan M R, Anower M S, Islam M A & Razzak S M A, *Appl Opt*, 55 (2015) 4145.
32 Islam R, Habib M S, Hasanuzzaman G K M, Rana S, Sadath M A & Markos C, *IEEE Photon Technol Lett*, 28 (2016) 1537.
33 Islam R, Rana S, Ahmad R & Kaijage S F, *IEEE Photon Technol Lett*, 27 (2015) 2242.
34 Isalm Md Sohidul, Reza K M S & Islam M R, *Indian J Pure Appl Phys*, 56 (2018) 399.
35 Issa N A, Eijkelenborg V M A, Fellew M, Cox F, Henry G & *Large M C*, *Opt Lett*, 29 (2004) 1336.
36 Pysz D, Kujawa I, Stepien R, Klimczak M, Filipkowski A, Franczyk M, Kociszewski L, Buzniak J, Harasny K & Buczynski R, *Bull Pol Ac Technol*, 62 (2014) 667.
37 Islam R, Hasanuzzaman G K M, Habib M S, Rana S & Khan M A G, *Opt Fiber Technol*, 24 (2015) 38.