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***Abstract*— In this paper, a high dispersion compensating photonic crystal fiber (PCF) has been proposed, fabricable with simple fabrication schemes. The lattice design structure is comprised of five rings of circular air-holes. The rings are arranged with an octagonal geometry. The fiber exhibits an ultra-high negative dispersion, that cancels the accumulated positive material and group velocity dispersion, such that the transmitted optical signal remains almost undistorted. The full vector finite element method (FEM) incorporated with a circular, perfectly matched layer (PML) at the boundary is implied to investigate the different optical properties of the proposed fiber. The numerical simulation of the designed fiber indicates that an ultra-high negative dispersion of –3112 ps.nm^{-1}.km^{-1} at 1.55µm wavelength can be obtained, which can reduce the length of dispersion compensating fiber significantly. Besides, the structural diameter deviation of ±2% over the optimum value of the proposed PCF is evaluated for investigating fabrication flexibility. Moreover, the proposed fiber exhibits high nonlinearity of 94.89 W^{-1}km^{-1}at 1550 nm wavelength, which makes the proposed fiber a suitable candidate for optical back-propagation application, super-continuum generation, and high-bit-rate optical transmission system.**

Keywords*— *dispersion, fiber optic transmission, non-linearity, octagonal PCF, photonics, photonic crystal fiber

I. Introduction

PCFs have been extensively studied for overcoming the major pitfall of ordinary optical fibers as they possess superior optical characteristics which include dispersion properties, high birefringence, high nonlinearity, and endless single-mode effects. PCF microstructures [1] in general consist of regularly arrayed air holes running down their entire length. By controlling the structure of air-holes or lattice geometry of the cladding, PCFs have established remarkable optical properties, which are improbable to be attained in ordinary fibers.

In high-speed conventional optical communication systems, the leading pitfall is known as dispersion. This dispersion, along with conventional single-mode fibers needs to be compensated to avoid inter-symbol interference. Dispersion compensating fibers (DCFs) is used as one of the most efficient and effective methods to overcome this constraint. However, conventional DCFs are unlikely to produce large negative dispersion. Meanwhile, PCFs ensure large negative dispersion. Another optical property, nonlinearity is one of the most significant characteristics which qualify PCF to be a notably hot topic of research interest in recent years. Currently, in numerous implications, for example, supercontinuum generation, optical parametric amplification, conversion of wavelength, and so on, highly nonlinear PCFs are vital candidates [2].

Birks et al. came up with the concept of utilizing PCF for the compensation of dispersion (*D*) for the high-speed optical transmission system. They proposed a PCF D = −2000 ps.nm^{-1}.km^{-1}with a smaller core area. Recently, various PCFs have proposed to attain significant negative dispersion and nonlinearity. For example, in 2013, Anwar et al. reported a modified octagonal structure having six air holes shaped as an ellipse which were present centrally in the core to such that *D* = -588 ps.nm^{-1}.km^{-1} along with a birefringence (*B*) = 0.0181 at 1550nm [3]. Hasan et al. reported an octagonal structure PCF having an elliptical-shaped core and revealed negative dispersion of -544.7 ps.nm^{-1}.km^{-1} for an operating wavelength (λ) = 1550 nm in 2014 [4]. However, it becomes quite vital to consider the drawbacks of these designs which include the fabrication issue and the smaller dispersion coefficient. In 2015, Habib et al. came up with a novel highly nonlinear PCF, capable of dispersion compensation using hybrid lattice design [5]. Somne et al. have designed a double octagonal lattice PCF using four air holes shaped as an ellipse and five annular rings in the cladding and the reported *D* = -211ps.nm^{-1}.km^{-1} at 1.55µm in 2016 [6]. In 2018, Redwan et al. have designed a modified octagonal structure using a double row non-circular shape core to achieve significant dispersion over 300 nm flat band [7]. Biswas et al. [8] designed a single novel mode all circular air holes PCF using hexagonal geometry which attained a dispersion around -753.2 ps.nm^{-1}.km^{-1}. A square PCF lattice structure had been revealed by Islam et al. in 2019 in which the reported dispersion is -2015.30 ps.nm^{-1}.km^{-1} at 1.55µm [9]. In 2019, Biswas et al. [10] also came up with an octagonal PCF where they achieved *D* = -1449 ps.nm^{-1}.km^{-1}. Recently, we have designed a novel bored core hexagonal PCF by taking into account fabrication simplicity and found a $D = -2102$ ps.nm^{-1}.km^{-1} at λ=1.55μm.

As part of ongoing research in obtaining a new improved PCF lattice design such that an ultra-high negative dispersion is exhibited, in this paper, a simple design of octagonal PCF with asymmetric air hole diameter near the core are numerically investigated using full vector FEM. The proposed PCF lattice structure utilizes only annular air-holes, taking the simplicity of fabrication and cost into account. Our numerical investigation exhibits a highly negative dispersion of – 3112 ps.nm^{-1}.km^{-1} at 1550 nm. The PCF also obtains a comparatively high nonlinearity of 94.89 $W^{-1}km^{-1}$ at 1.55μm wavelength.

II. Design Structure Of The Proposed Octagonal PCF (OPCF)

Fig. 1 shows the proposed index guiding of the Octagonal PCF (OPCF). The lattice structure contains five rings. The background material was chosen to be silica. Seven additional air-holes of reduced diameter were introduced in the core area to enhance the dispersive properties of the fiber. These seven annular rings change the refractive index profile for the core mode, which in turn provides better modal properties of the designed fiber due to the fact that dispersion properties are greatly influenced by the air-holes size and position near the core region. The total geometrical structure consists of four different diameter values (d_0, d_1, d_2, and d_3). Adding extra air holes near the core area affects the optical properties of PCF significantly. Furthermore, the optical property variations are also studied with respect to the variations in the global parameters for compatibility with the fabrication process. Therefore, by properly tuning the geometrical structural parameters of the proposed octagonal PCF, it can obtain ultrahigh negative dispersion features in particular wavelength regimes [4,9].

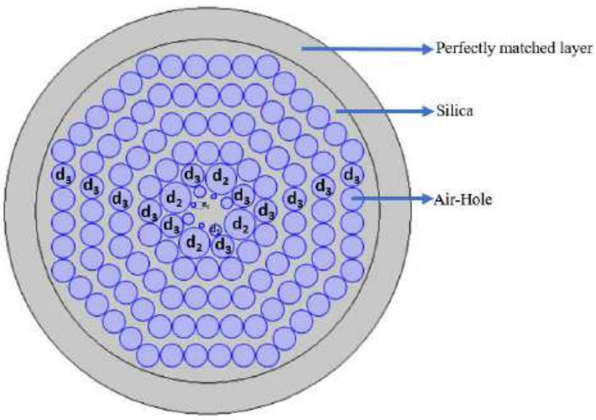

Fig.1 Cross-section of the designed PCF

III. Numerical Method

The full-vector Finite Element Method (FEM) software, COMSOL Multiphysics has been utilized as a numerical simulation tool to study the different optical characteristics of the designed PCF. A perfectly matched layer (PML) in circular shape has been placed on the exterior side of the outermost ring to evade reflection and backscattering and improve light confinement inside the core. The background material is formed of silica, and the refractive index has been obtained by employing the following Sellmeier's equation:

$$n(\lambda) = \sqrt{1 + \sum_{i=1}^{N} \frac{B_i \lambda^2}{\lambda^2 - C_i}} \tag{1}$$

Here, B_i and C_i are Sellmeier's coefficients and N=1,2,3. The modal effective refractive indices n_{eff} are related to the propagation constants:

$$n_{eff} = \frac{\beta(\lambda, n_m(\lambda))}{k_0} \tag{2}$$

Here, chromatic dispersion $D(\lambda)$ depends on the real part of n_{eff}, and the dispersion has been obtained by following expression [20-21]:

$$D(\lambda) = -\frac{\lambda}{c}\frac{d^2 Re[n_{eff}]}{d\lambda^2} \tag{3}$$

Here, c denotes light velocity in vacuum. However, the nonlinearity largely depends on the effective area A_{eff}. The effective area A_{eff} is dependent on the electric field profile.

$$A_{eff} = \frac{(\iint |E|^2 dxdy)^2}{\iint |E|^4 dxdy} \tag{4}$$

Here, E denotes electric field intensity. The impact of nonlinearity γ on the proposed PCF structure was measure by using effective mode area A_{eff}. The relationship γ and A_{eff} can be expressed using the following expression:

$$\gamma = \frac{2\pi}{\lambda} \times \frac{n_2}{A_{eff}} \tag{5}$$

Here, n_2 is the Kerr constant.

IV. Simulation Results And Discussion

This section portrays the numerical investigation of the optical properties of our lattice design by tailoring the optimum design parameters. Fig. 2 demonstrates the fundamental optical mode field profile at λ=1550nm for the two orthogonal polarization modes. As seen from the figure, dark red colour depicts that both the modes are solely bound in the central core region. This phenomenon occurs for having the right amount of index contrast between the center and the cladding.

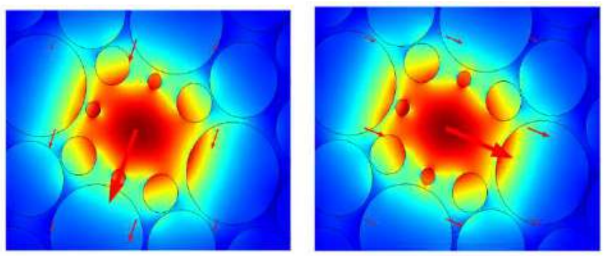

Fig. 2. Intensity profiles of fundamental modes at the 1550 nm wavelength (a) x-polarization (b) y-polarization

Fig. 3 portrays the gradual change of the negative dispersion induced in the PCF design through the geometric structure in the spectral range corresponding to the wavelength from 1350 nm to 1600 nm with optimum pitch Λ =0.76μm. From this figure, it can be noticed that the proposed structure with the optimum design parameters allow the structure to achieve large dispersion from −910.40 ps.nm^{-1}.km^{-1} to −3112 ps.nm^{-1}.km^{-1} and −920.40 ps.nm^{-1}.km^{-1} to −3112 ps.nm^{-1}.km^{-1} for the faster and slower axes, respectively over 1350 to 1600 nm wavelength. As per the simulated result, it is apparent that the PCF shows significant $D = -$ 3112 ps.nm^{-1}.km^{-1} for both axes at 1.55 µm wavelength. The chromatic or material dispersion is calculated via equation 3. The mathematical model suggests that the effective refractive index of the core mode is changing in such a way that the double derivative of the change of the effective index with respect to the incident wavelength of light induces a negative dispersion coefficient for the optical fiber. The 4 reduced diameter air-holes in the core region break the circular symmetry of the fiber. This causes the incident light to get polarized into two orthogonal x and y polarization modes while passing through the fiber. The basic optical physics for the rest of the analysis is based on this phenomenon.

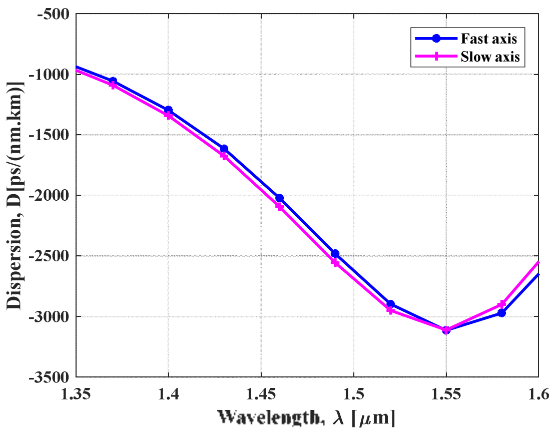

Fig. 3. D vs wavelength for x and y polarizations.

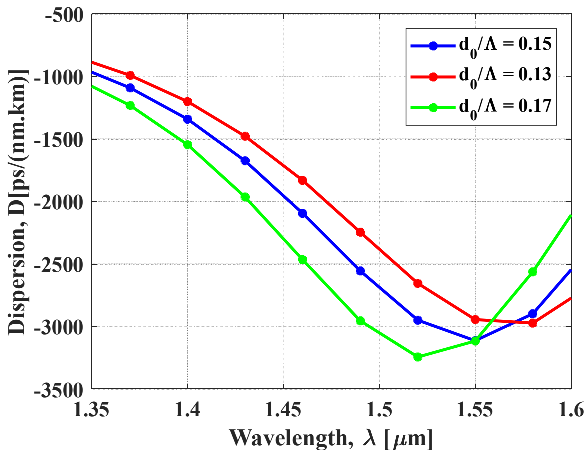

Fig. 4. Dispersion characteristics for of d_0/Λ variations.

Fig. 4 shows the variation in the dispersion properties of the designed microstructure, over the entire λ range of 1.35µm to 1.6µm, due to change in d_0/Λ = 0.13, 0.15, and 0.17 keeping the other parameters remained fixed. The calculated dispersion is -2945 ps.nm^{-1}.km^{-1}, -3112 ps.nm^{-1}.km^{-1}, and -3116 ps.nm^{-1}.km^{-1}, respectively at 1.55µm. The observation of the data clearly demonstrates that the negative dispersion decreases with the increase of d_0. The optimum design parameters have been chosen as pitch Λ=0.76µm, d_1/Λ=0.37, d_2/Λ=0.99, and d_3/Λ=0.73. It has also been observed that varying the air-hole diameter d_0 has a much lesser impact on dispersion properties. Fig. 5 shows the dispersion values of -2603 ps.nm^{-1}.km^{-1}, -3112 ps.nm^{-1}.km^{-1}and -2964 ps.nm^{-1}.km^{-1}when d_1/Λ is set to 0.35, 0.37 and 0.39 respectively keeping the other parameters constant. The other optimum parameters have been taken to pitch Λ=0.76µm, d_0/Λ=0.15, d_2/Λ=0.99, and d_3/Λ=0.73. The simulation result shows that varying the air-hole diameter d_1 led to significant deviations in the characteristics of dispersion as compare to diameter d_0 at 1.55 µm due to the fact that d_1 creates more asymmetry inside the core to alter the refractive index significantly.

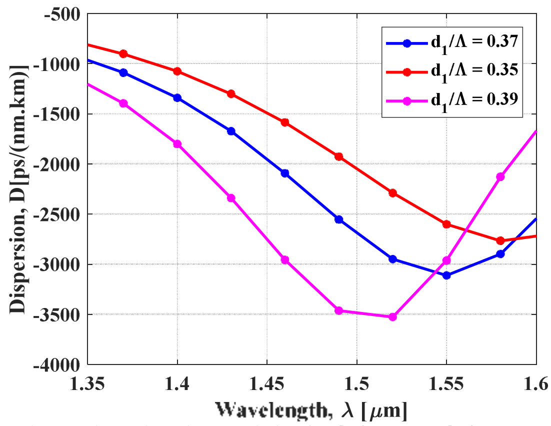

Fig. 5. Dispersion characteristics for d_1/Λ=0.37, d_1/Λ=0.35 and d_1/Λ=0.39.

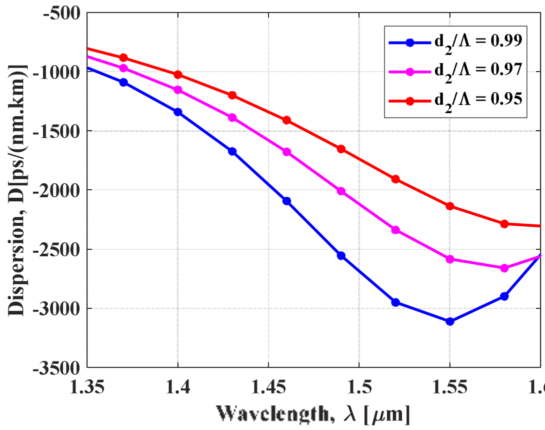

Fig. 6. Dispersion features for d_2/Λ=0.99, d_2/Λ=0.97 and d_2/Λ=0.95.

Now, the D can also be investigated by changing the air-hole diameter d_2 while Λ=0.76 µm, d_0 = 0.15Λ, d_1 = 0.37 Λ, d_3 =0.73 Λ is kept constant is shown in Fig. 6. The dispersion at 1.55 µm wavelength has been observed as -2137 ps.nm^{-1}.km^{-1}, -2585 ps.nm^{-1}.km^{-1}, and -3112 ps.nm^{-1}.km^{-1} for the d_2/Λ values of 0.95, 0.97, and 0.99, respectively. Further investigation has been performed on dispersion characteristics by varying d_3 of the designed structure shown in Fig. 7. The result reveals that with a constant optimum value of the pitch Λ =0.76 µm, d_0 = 0.15

Λ, d_1 = 0.37Λ, and d_2 =0.99Λ, the dispersion at 1.55 μm is -1623 $ps.nm^{-1}.km^{-1}$, -3112 $ps.nm^{-1}.km^{-1}$, and -2174 $ps.nm^{-1}.km^{-1}$ while d_3 /Λ values of 0.71, 0.73, and 0.75, respectively. The alterations for air-hole diameter d_3 show a significant change in dispersion characteristics.

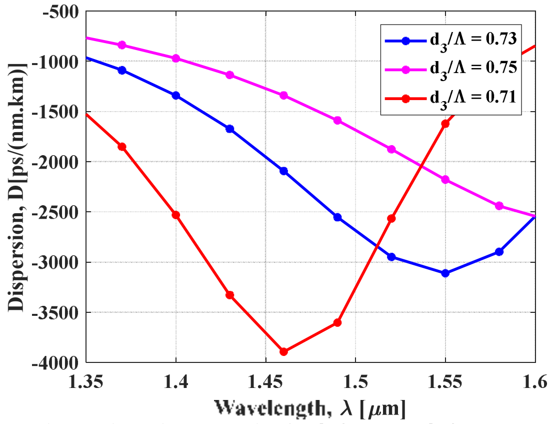

Fig. 7. Dispersion properties for d_3/Λ=0.73, d_3/Λ=0.75 and d_3/Λ=0.71.

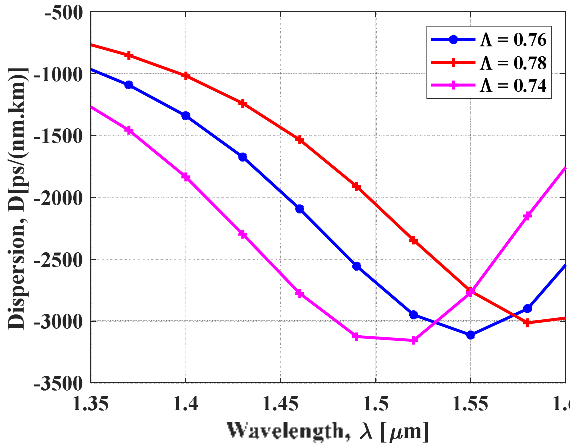

Fig. 8. Influence of pitch, Λ variation on dispersion characteristics.

Fig. 8 portrays the change in the negative dispersion corresponding to the variations brought in the value of the pitch. The observation of the data clearly demonstrates that the proposed design process significant variations in dispersion features. Fig. 9 portrays the dispersion features by scaling down the parameter pitch in the tolerance range of ±1 to ±2%. It is to be noted that pitch Λ does not induce significant variation at 1.55 μm which ensures promising dispersion tolerance after fabrication. Hence, the pitch variations up to ±2% have been studied, and corresponding change brought about in the modal properties has been observed.

The effective area of the core mode has a reciprocal relationship with the non-linear coefficient of the fiber. A reduced effective area induces a higher non-linearity for the light passing through the fiber. The presence of surplus air-holes in the cladding can generate high non-linearity by keeping the effective modal area reduced.

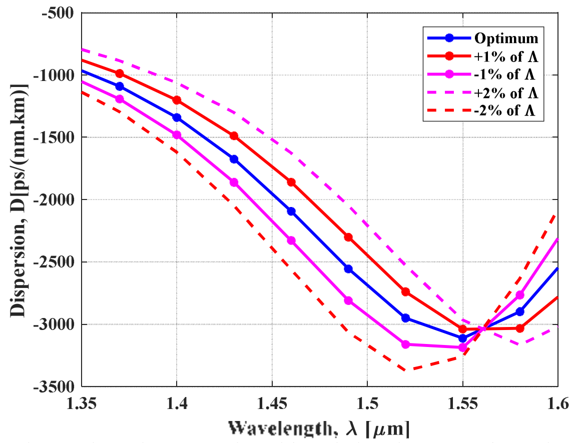

Fig. 9. Dispersion properties with variations in ±1% and ±2% in pitch.

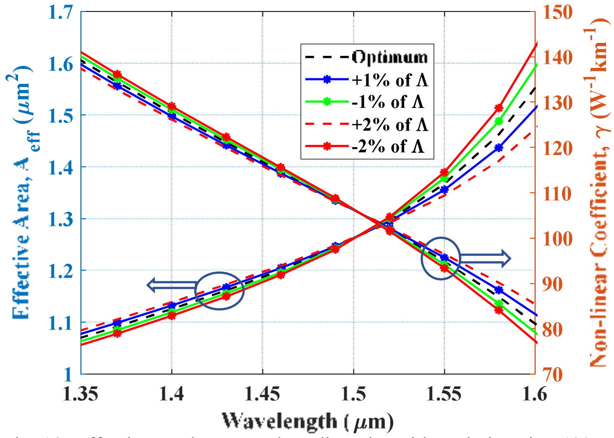

Fig. 10. Effective mode area and nonlinearity with variations in ±1% and ±2% in pitch.

Fig. 10 illustrates the sensitivity of the optical characteristics which include the effective area and the nonlinearity of the lattice design. From the graphical observations, it is evident that the effective mode area is 1.367 μm^2 at λ=1550 nm. According to Fig. 10, the effective area varies about ±0.025 μm^2 for ±1% variation in pitch, ±0.05 μm^2 for ±2% variation in pitch parameter. Furthermore, for the effective mode area and nonlinearity, there is hardly any significant change with respect to the ±1% and ±2% variations brought about in the value of the pitch, Λ. Hence, the pitch variations up to ±2% have been studied and corresponding change brought about in the modal properties has been observed. It can be concluded from this analysis that the fiber shows good fabrication tolerance.

Reference	Year	Dispersion, $ps.nm^{-1}.km^{-1}$	Air-hole Shape	Geometrical Structure	Number of Rings & Degree of Freedom
[8]	2018	-753.2	Circular	Hexagonal	5, 3
[9]	2019	−2015.30	Circular	Square	5, 4
[10]	2019	-1449	Circular	Octagonal	5, 3
[11]	2019	– 2102	Circular	Hexagonal	5, 4
[15]	2020	-2221	Circular & Elliptical	Hexagonal	5, 3
Proposed PCF	2020	−3112	Circular	Octagonal	5, 5

Finally, table 1 makes a comparative argument of this work with recent publications of PCF in literature with respect to the dispersion at 1.55 μm by taking into account the annular shape, geometrical structure, and the number of rings and degrees of freedom. Our proposed PCF has been set up with all circular air-holes, which facilitates the fabrication process as simple as possible. Some of the works presented in the table have been able to achieve somewhat larger dispersion values, but our results have surpassed those values to a significant extent. Also, the design has an upper hand in terms of the fabrication process, as mentioned earlier.

The dispersion in high-speed optical broadband communications can be compensated using our proposed octagonal photonic crystal fiber (OPCF), as portrayed in Fig. 11. The positive dispersion of the transmission fiber (TF) can be compensated by introducing a dispersion compensating PCF (DC-PCF) with equal negative dispersion into the communication system. The total dispersion of the communication system, which is actually 0, can be calculated as follows:

$$D_{Total} = D_{TF}L_{TF} + D_{DC-PCF}L_{DC-PCF} \tag{6}$$

$$D_{TF}L_{TF} = -D_{DC-PCF}L_{DC-PCF} \tag{7}$$

The overall dispersion in the TF of any metropolitan area can be tuned using a short length DC-PCF. The proposed ultra-high dispersion compensating photonic crystal fiber consists of one 183Km long TF, an amplifier to amplify the weak signal, and a small length of 1Km DC-PCF at an excitation wavelength of 1550nm.

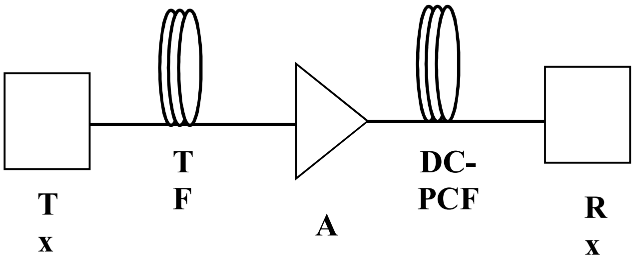

Fig. 11. Basic optical fiber communication system for dispersion compensation consisting of TF, A, and DC-PCF. Tx= transmitter, Rx= Receiver.

Finally, we found the feasibility of the fabrication of the proposed PCF structure. Several well-established techniques such as conventional sol-gel casting, drilling, and stack and draw method have been reported for PCF fabrication. To tune the dimension and the arrangement of the annular rings in circular shape geometry, the drilling technique is used widely in the fabrication process. The established stack and draw technique are applied for closed packed lattice geometry, where the core structure can be controlled easily. Bise et al. [16] demonstrated a sol-gel technique for fabricating complex structures, including elliptical or rectangular air-holes. Our proposed PCF contains the smallest air-holes in diameter of 0.114 μm. In 2007, Wiederhecker et al. [12] used to stack and draw technique to fabricate air-holes in diameter of 0.110 μm. Our proposed design only consists of circular air holes. Therefore, conventional drilling or stack and draw technique are the viable methods for constructing our proposed structure in a feasible way.

With the recent advancement in fabrication technology, it is possible to modify the silica background geometry with pulsed lasers and side polishing techniques [17,18]. The most recent published PCF model uses a five-ring hexagonal photonic crystal arrangement [19]. There is the presence of reduced diameter air-holes arranged in 2 rings, which has been the key to achieving high negative dispersion. However, their achieved negative dispersion is -2159ps.nm^{-1}km^{-1} at 1.55μm wavelength, which is still not as low as that of ours. Another recently published work has attained a negative dispersion close to -800 psnm^{-1}km^{-1} at 1.1μm wavelength [20]. However, at 1.55 μm, which is pretty much required for optical broadband communication, the structural chromatic dispersion significantly deteriorates and induces positive dispersion. They have used a similar 5ring octagonal geometry. But their photonic crystal arrangement was not up to the mark.

V. CONCLUSION

This work comes forward with a PCF model, which is directly suited for its usage in broadband optical communications. The fiber's capability to generate a very high negative dispersion of -3112 ps.nm^{-1}.km^{-1} at 1.55 μm wavelength suggests that octagonally arranged five-ring air-hole photonic crystal arrangements belong to the most eclectic designs of optical fibers. The model consists of only circular air-holes, which are easily fabricable with the existent stack and draw and so-gel methods. This paper shows a detailed analysis of its optical properties. Moreover, we have also come forward with a technical analysis of fabrication tolerance on our proposed design structure. The PCF model delineates that it has a very high non-linear coefficient as well. This makes the fiber an eligible candidate for its usage in sensing, supercontinuum generation and high bit-rate optical transmission system.

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