Numerical Studyof an Octagonal Photonic Crystal Fiber: An Improved Design

Mohammad Mahmudul Alam Mia[1], Delowar Hossain Himel[2], Shovasis Kumar Biswas[2,*]
[1]Department of Electronics and Communication Engineering, Sylhet International University, Bangladesh
[2]Department of Electrical & Electronic Engineering , Independent University, Bangladesh
*biswassk@iub.edu.bd, shuvoapece@gmail.com

***Abstract*— We numerically demonstrate an improved photonic crystal fiber using octagonal structure due to its achievement in ultra-high negative dispersion value and large nonlinearity simultaneously. For analysis and inspection, the guiding properties of PCF, Finite Element Method (FEM) with perfectly matched layer is used. It is reported that the designed structure exhibits a large dispersion of -2012 ps.nm^{-1}.km^{-1} at 1550nm wavelength. Due to structural simplicity and improved dispersion properties, the designed PCF can be easily fabricated. In addition, the proposed structure makes itself suitable for sensing, dispersion compensation and super continuum generation.**

Keywords—Octagonal PCF, Chromatic Dispersion, Nonlinearity.

I. INTRODUCTION

PCF have some extra-ordinary characteristics such as high birefringence and non-linearity, little loss of confinement with enlarged effective mode area compared to other general optical fibers. Those properties have drawn everyone's attention nowadays [1-3]. Usually micro or nano structure PCF's can be designed with air holes lattices enclosed by silica. But these structures can be modified by using air hole with different shapes and arrangement to achieve the ultra-high birefringence property. Recently, different types of air holes arrangement have proposed for getting large negative dispersion and large nonlinearity for the application of sensing and optical back propagation. Razzak et.al have proposed a single mode PCF to gain highly negative dispersion and nonlinearity by using FEM based on hybrid structure. They selectively omitted the air holes in the core to enhance the optical properties and reported negative dispersion co-efficient of -555.93 ps /nm.km at wavelength of 1550 nm [4]. In 2017, Islam et al. designed a novel PCF using circular and elliptical air-holes based on square-lattice structure that achieves a dispersion of -1528.5 ps.nm^{-1}.km^{-1} at 1.55μm wavelength [5]. However, major pitfall of this design is fabrication process. In 2019, Biswas et al. [7] designed a novel all circular air holes PCF using square geometry and reported dispersion of -886 ps.nm^{-1}.km^{-1} at 1.55μm wavelength.

As part of ongoing research in obtaining a new improved PCF structure with an ultra-high negative dispersion, in this paper a simple design of octagonal PCF with asymmetric air hole diameter near the core are numerically investigated using full vector finite element method. The proposed PCF architecture used only circular air-holes by taking into account fabrication simplicity and cost. The simplicity in the fabrication process coupled with significant dispersion and nonlinearity of our designed PCF make it a strong candidate for super continuum generation, and optical amplification

II. GEOMETRIC REPRESENTATION AND NUMERICAL MODELING

The proposed design has an octagonal photonic crystal arrangement, with a five rings of airholes. The designed O-PCF has three different diameters d_0, d_1, and d_2. This configuration is used in the proposed PCF to find out the different geometrical characteristics. This type of design contains 4 parameters (d_0, d_1, d_2, and Λ) in which there are 3 different air hole diameters where d_0 is relatively smaller than d_1, and d_2. The pitch, Λ is referred to the adjacent distance between the center of the air holes. An asymmetry is introduced in first ring in order to achieve ultra-high negative dispersion. The material used for the proposed structure is silica and this arrangement simultaneously increasing the non-linearity and dispersion without introducing any rectangular or elliptical air holes in the first ring which makes the design easier to fabricate.

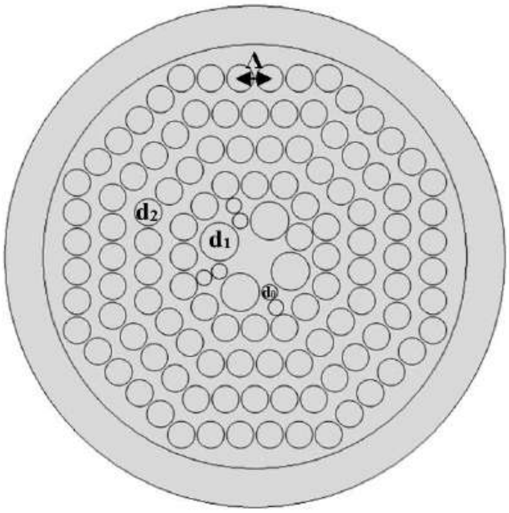


Fig. 1. Cross section of the designed O-PCF.

FEM software and COMSOL Multi-physics for full vector has been used to handle the proposed O-PCF model analysis and its simulation. In this part some important terms of designing the PCF will be narrated. The most effective refractive index value is found by solving the Maxwell vectorial equation. This effective refractive index is used to calculate dispersion D by using the given below equation.

$$D(\lambda) = -\lambda / c(d^2 \operatorname{Re}[n_{eff}] / d\lambda^2)$$

Where n_{eff} is the functional relation between wavelength and material dispersion. n_{eff} can be obtained from

$$n_{eff} = \beta(\lambda, n_m(\lambda))/k_0$$

where β=constant of propagation, k_0 = no. of wave in the free space ($k_0=2\pi/\lambda$).

However, nonlinear coefficient γ is calculated using the following formula

$$\gamma = \left(\frac{2\pi}{\lambda}\right)\left(\frac{n_2}{A_{eff}}\right)$$

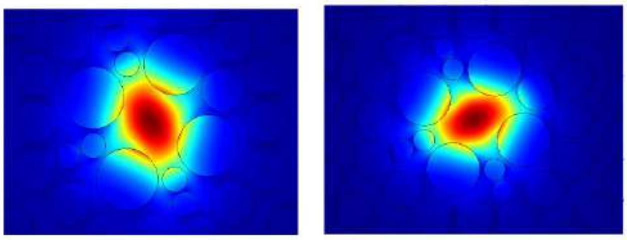
where, effective area A_{eff} is determined using the equation

$$A_{eff} = \left(\iint |E|^2 dxdy\right)^2 / \iint |E|^4 dxdy$$

Here E is defined as the electric field.

III. Numerical Analysis

Figure 2 displays the fundamental mode field profile for the designed PCF in the x and y polarization modes when the excitation wavelength is tuned to 1550nm. For the dispersion compensation of broadband, it shows that the dispersion curve is negative. The result of the experiment shows that the light is strictly restricted in the core area. The gain of dispersion coefficient of the experiment is -2012 ps/(nm.km) at 1.55μm wavelength for y polarization.



(a) (b)

Fig. 2: Distribution of optical field at 1550nm for (a) fast axis and (b) slow axis.

A. *Influence of the fiber parameters on dispersion*

Figure 3 indicates the variation of pitch and its effect on the dispersion behavior when the diameters of air holes are kept constant. In the proposed O-PCF the variations of pitch are taken as 0.76μm, 0.78μm, 0.80μm. Now the resulted dispersion coefficient at the operating wavelength 1550nm are -2012, -1893 and -1671, respectively. It is clearly seen that the chromatic dispersion is highly negative, and it can be gained if the pitch is reduced from 0.8μm to 0.76μm. It is predicted that the proposed O-PCF is enabling to countervail the dispersion coefficient and obviously which is better than [7].

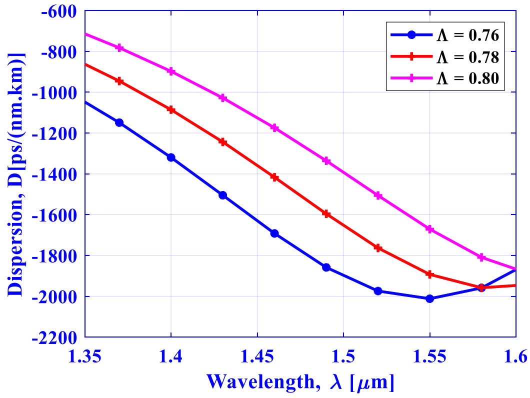


Fig. 3: Impact of pitch, Λ on dispersion properties.

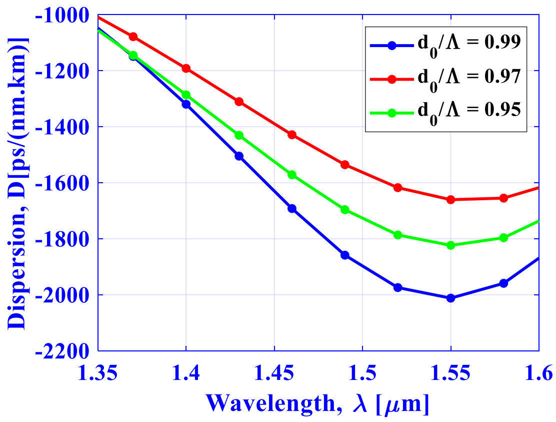


Fig. 4: Effect of dispersion by varying diameter of d_0.

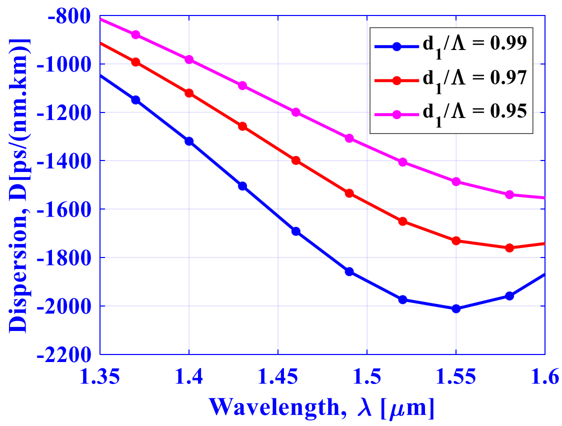


Fig. 5: Effect of dispersion by varying diameter of d_1.

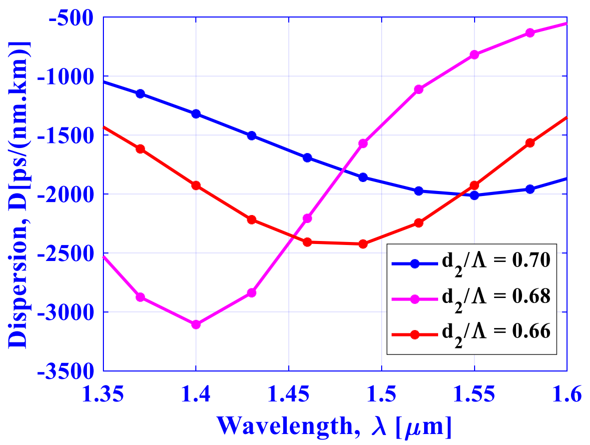


Fig. 6: Effect of dispersion by varying diameter of d_2.

Figure (4-6) shows the diameter variation on dispersion characteristics. Three different types of diameter (d_0/Λ, d_1/Λ, and d_2/Λ) are changed to analysis the dispersion characteristics of the designed O-PCF. While considering one diameter to analysis the dispersion behavior, other two diameters are kept fixed. In all cases optimum value of dispersion is fixed regardless of the diameter variation. Fig. 7 reveals the pitch tolerance on dispersion characteristics. Pitch tolerance can be considered to be the most effective way to check the fabrication feasibility. In the fabrication process it can be varies ±1% of global diameter. It can be clearly observed that dispersion cannot significantly change with the pitch variation from ±1% to ±2%.

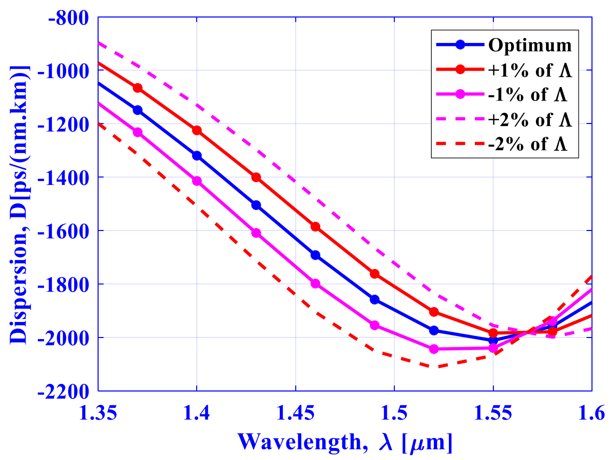


Fig. 7: Dispersion properties with variations in ±1% and ±2% in pitch

B. *Influence of the fiber parameters on effective area and nonlinearity*

Fig. 8 reveals the impact of pitch on effective area and nonlinearity by keeping other parameters are fixed. Effects of nonlinear can become momentous even at endurable optical powers as well as data bit rates. Though the signal proclaims through the fiber, the power of the signal decreases due to attenuation. Maximum effects of nonlinear occurs in the commencement of the fiber. To understanding about the non-linear term in PCFs knowing about effective area A_{eff} is a must. The relation between effective area and non-linear coefficient is inversely proportional. The result of simulation is clearly showing that the result of nonlinear coefficient is 96.67 $W^{-1}km^{-1}$ at 1.55μm wavelength. This nonlinear behaviour has a so many applications like pulse-forming, wavelength conversion, supercontinuum generation etc.

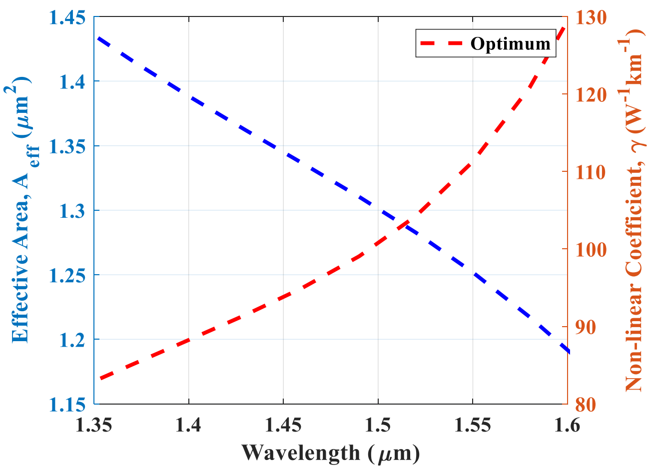


Fig. 8: Effective mode area and non-linearity vs wavelength for optimum parameters.

TABLE I. COMPARATIVE REPRESENTATION OF DIFFERENT PCFS.

Ref. No.	***Dispersion***	***Nonlinearity***	**Air-Hole shape**
[4]	-555.93	40.1	Circular
[5]	-1528.5	84.80	Circular& Elliptical
[6]	-886	91.25	Circular
[7]	-650	45.5	Circular
Proposed PCF	-2012	96.67	Circular

IV. COMPARATIVE STUDY AND FABRICATION ISSUE

Finally, from Table 1, we can compare our proposed O-PCF properties with other related contemporary PCF structures. We have shown the comparison in Table 1 in terms of nonlinearity, air-hole shape, and dispersion at wavelength 1550nm. There is another comparison of fabrication feasibility based on air holes cladding where shapes of air holes matter. From Ref. 5 we have seen that they reported dispersion of -1528 using non-circular air-holes. Thus, the proposed design has highest dispersion compared with recent PCFs. Hence the smaller span of fiber and easy fabrication will be available on practical application. The main challenge of any PCF design is to ensure the fabrication simplicity. Method of drilling is usually used for little numbered air holes on PCF. Another challenge is noncircular air holes fabrication because highest feasibility limited for rounded holes of air cladding. To re-shape the air holes from circular shape, there may be in change in pressure, surface tension which can change the performance of PCF. Our proposed PCF can be used in optical microcavity due to large nonlinearity [8].

V. Conclusion

In this work, an octagonal PCF structure is proposed and numerically investigated. To investigate the optical guiding properties of the designed PCF numerically, finite element method-based software Comsol Multiphysics is used. The designed O-PCF exhibits high nonlinearity and ultrahigh negative dispersion of 96.67 $W^{-1} m^{-1}$ and -2012 $ps.nm^{-1}.km^{-1}$, respectively at 1550nm which is much better than the recent results. Additionally, variation in various structural parameters like pitch, and air hole diameter is also analyzed. The proposed all circular octagonal PCF may be suitable for dispersion compensating fiber to compensate dispersion, and super continuum generation [9, 10].

References

[1] J. C. Knight, "Photonic crystal fibers and fiber lasers." JOSA B 24, no. 8, pp. 1661-1668, 2007.

[2] S. K. Biswas, R. Arfin, A. B. Habib, S. B. Amir, Z. B. Zahir, M. R. Islam, and M. Hussain. "A modified design of a hexagonal circular photonic crystal fiber with large negative dispersion properties and ultrahigh birefringence for optical broadband communication." In Photonics, vol. 6, no. 1, p. 19. Multidisciplinary Digital Publishing Institute, 2019.

[3] H. Talukder, M. I. A. Isti, S. Nuzhat, and S. K. Biswas. "Ultra-High Negative Dispersion Based Single Mode Highly Nonlinear Bored Core Photonic Crystal Fiber (HNL-BCPCF): Design and Numerical Analysis." Brazilian Journal of Physics: 1-9, 2020.

[4] M. I. Hasan, M. S. Habib, M. S. Habib, and S. A. Razzak. "Highly nonlinear and highly birefringent dispersion compensating photonic crystal fiber." Optical Fiber Technology 20, no. 1, pp. 32-38, 2014.

[5] M.I. Islam, M. Khatun, K. Ahmed, Ultra-high negative dispersion compensating square lattice based single mode photonic crystal fiber with high nonlinearity, Opt. Rev. 24, 2017.

[6] M. M. Faruk, M. A. Hossain, M. Rahman, and S. K. Biswas. "Ultra-high birefringence and highly nonlinear dispersion compensating square photonic crystal fiber for fiber optic transmission systems: Design and analysis." In 2019 10th International Conference on Computing, Communication and Networking Technologies (ICCCNT), pp. 1-4. IEEE, 2019.

[7] S. K. Biswas, T. Ahmed, M. Ahmed, M. S. Miah, M. T. I. Opu, and F. Wahid. "Broadband Dispersion Compensating Highly Nonlinear Square Photonic Crystal Fiber: Design & Analysis." In 2019 Innovations in Power and Advanced Computing Technologies (i-PACT), vol. 1, pp. 1-5. IEEE, 2019.

[8] Biswas, Shovasis. "Impact of Kerr and Raman nonlinear effects on the whispering gallery modes of a spherical microcavity." PhD diss., 2016.

[9] K. Labeeb, and S. K. Biswas. "Numerical Investigation of Ultra-high Negative Dispersion Compensating Octagonal Photonic Crystal Fiber With High Nonlinearity." In 2019 10th International Conference on Computing, Communication and Networking Technologies (ICCCNT), pp. 1-5. IEEE, 2019.

[10] M. M. Faruk, Md R. Islam, S. M. R. Islam, M. Ahmed, M. S. Miah, and S. K. Biswas. "Ultra-high Negative Dispersion Compensating Index Guiding Single Mode Octagonal Photonic Crystal Fiber: Design and Analysis." In 2019 Innovations in Power and Advanced Computing Technologies (i-PACT), vol. 1, pp. 1-5. IEEE, 2019.