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# Highly Nonlinear Dispersion Compensating Octagonal Photonic Crystal Fiber: Design and Analysis

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***Abstract*—In this paper, we have presented an octagonal photonic crystal fiber (PCF) having five rings with circular air-holes of two different diameters which can yield high negative chromatic dispersion as well as high nonlinear coefficient. Finite element method has been employed to investigate the optical features of the designed PCF. The numerical investigation indicates that a large dispersion of -1449 ps/(nm.km) is obtained at λ = 1.55 µm which makes it suitable for compensating dispersion in optical communication networks. Moreover, the proposed PCF also offers high nonlinearity of 100.5W$^{-1}$Km$^{-1}$ at 1.55µm wavelength which makes it suitable for sensing application. Furthermore, structural parameter variation around appropriate value is investigated.**

***Keywords*—Photonic crystal fiber, Dispersion Compensating Fiber, Birefringence.**

## I. Introduction

Nowadays optical fibers are widely used in telecommunication networks and sensor technology. Light guided through optical fiber by total internal reflection (TIR). The core of the optical fiber must have higher refractive index than cladding in order to achieve TIR. But conventional optical fiber severely suffers for dispersion problem. In addition, they exhibit very small nonlinearity. In order to overcome this limitation of conventional optical fibers, a new fiber called photonic crystal fiber was recently proposed. The recent usage of photonic crystal fiber has started a new era of distortion less optical fiber communication. As a consequence, research on photonic crystal fiber has tremendously increased because of its unique physical properties including birefringence, non-linearity and negative chromatic dispersion [1].

Due to the higher efficiency of restituting chromatic dispersion, photonic crystal as dispersion compensating fiber has become a perfect replacement of conventional single mode optical fiber. This advantage of PCF is a consequence of its very high negative dispersion coefficient while conventional fiber cannot reduce the chromatic dispersion significantly. But fulfilment of this criteria is essential for long distance optical fiber communication [2-7]. Moreover, it is not possible to achieve commercially affordable length and fabrication cost of without having high negative dispersion [8,9]. Again, this criterion is also fulfilled by PCF architecture that makes it remarkably suitable material to fabricate optical links.

In order to investigate the perfect design of photonic crystal architecture, a notable amount of work and research has already been conducted [10-12]. PCF was first used as optical fiber material by Briks et al. [13] though the lattice architecture suffered from coupling-loss due to less effective area. Then a new S-PCF design proposed by Yang et al. [14] and showed a notable increase in nonlinear coefficient up to 68 W$^{-1}$Km$^{-1}$. After that Hasan et al. [15] and Haque et al. [17] proposed two separate PCF architecture representing gradual increase in birefringence and dispersion value up to 650 ps/ (nm.km). Then the usage of multi-shaped air-holes for cladding was observed and proposed by Islam et al. [18]. They used non-circular air-holes to achieve very high nonlinearity of 92.83 W$^{-1}$Km$^{-1}$ and dispersion of -1694 ps/ (nm.km).

In this paper we propose an octagonal PCF architecture that uses only circular air-holes for cladding to reduce the complexity of fabrication and production cost. The FEM was used to monitor the guiding parameters of the structure. The PCF showed large negative dispersion of -1449 ps/(nm.km) at λ = 1.55µm. It also provided comparatively higher nonlinearity of 100.5 W$^{-1}$km$^{-1}$ at 1.55µm wavelength.

## II. Geometrical Representation

The transversal view of our O-PCF design is shown in Fig. 1. The structure is designed using 5 octagonal rings of circular-shaped air-holes. The spatial distance between the centers of the two adjacent holes is denoted as pitch Λ. We choose pure crystalline silica ($SiO_2$) as the building material of air-holes considering the fact that it can significantly regulate the dispersion characteristics. The designed PCF includes only circular air-holes of two different diameters $d_1$ and $d_2$ for designing the structure. The hollow center of the structure is the inner core which is large enough to hold an air-hole of diameter $d_1$. Five octagonal air-hole rings encompass the core which are denoted altogether as cladding section. The number of holes from the outer-most to the inner-most ring are 40, 32, 24, 16 and 8, respectively. All holes of the cladding region have the same diameter $d_1$ except the inner-most ring which has two extra holes of diameter $d_2$ to prevent the dispersion of light out of the core.

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Thus, the suggested O-PCF structure achieves large negative dispersion and nonlinearity while reducing fabrication complexity as much as possible.

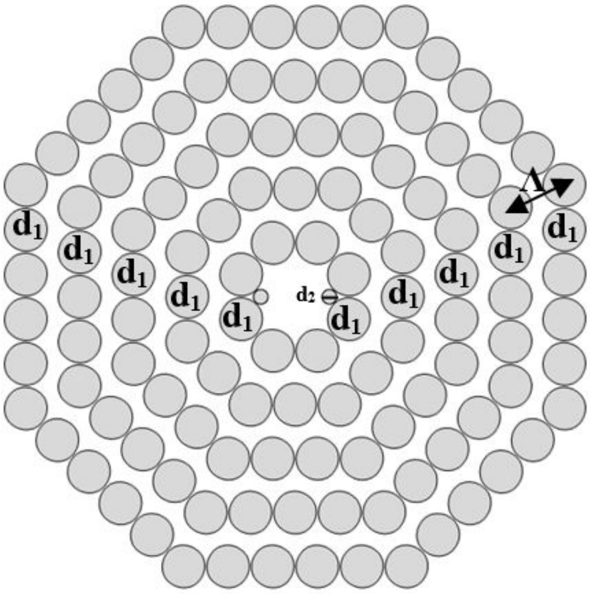


Fig. 1. Cross-section of O-PCF where Pitch, $\Lambda$ =0.77μm, $d_1/\Lambda$ =0.73, $d_2/\Lambda$ =0.25.

## III. Numerical Methods

A FEM based simulation tool, COMSOL Multiphysics version 5.3, is used to perform the numerical studies. A circular perfectly matched layer (PML) is employed at the boundary of the microstructure to simulate the optical properties. We used a 1μm uniform-PML around the proposed S-PCF, with scaling factor equals 1. The COMSOL Multiphysics software was used for numerical analysis of the optical characteristics while the Sellmier's equation was used to derive the dispersion coefficient of the proposed PCF shown in Eqn. 1

$$D(\lambda) = -\lambda / c(d^2 \,\mathrm{Re}[n_{eff}] / d\lambda^2) \tag{1}$$

Here, the chromatic dispersion and real-part of the effective refractive index are marked as D (λ) and Re ($n_{eff}$), respectively. The light-velocity in vacuum and wavelength of signal are marked as c and λ respectively. Then we calculate the birefringence using eqn. 2.

$$B = | n_x - n_y | \tag{2}$$

Here, the symbol B represents birefringence and the symbol $n_x$ and $n_y$ represents effective refractive index in polarization modes. Then we measure nonlinear coefficient using eqn. 3

$$\gamma = \left(\frac{2\pi}{\lambda}\right)\left(\frac{n_2}{A_{eff}}\right) \tag{3}$$

In eqn. 4, the symbol $\gamma$ represents the nonlinear co-efficient and the symbol $\lambda$ and $A_{eff}$ stand for wavelength and effective area respectively. The calculation of $A_{eff}$ is performed by using eqn. 4 where the symbol E represents the electric field.

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

We used different combinations to figure out the right magnitude of these parameters for optimum performance of the proposed PCF.

## IV. Results and Discussion

Fig. 2(a) and Fig. 2(b) show the distribution of the optical field at excitation wavelength of 1.55 μm for two orthogonal polarization modes. As we can see that the smaller air-holes of diameter $d_2$ helps the inner-most ring to prevent dispersion. We regulated the light wavelength at 1.55μm for the visualization process of the optical field distribution analysis.

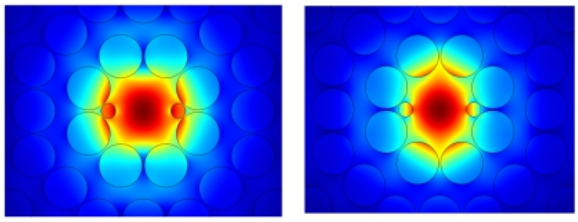

Fig. 2. Distribution of optical field (a) x-polarization and (b) y polarization.

Fig. 3 illustrates the dispersion characteristics of propound crystal structure for wavelength ranging from 1.35 μm to 1.6 μm. Significant development in negative dispersion with the increment of wavelength was noticed here. But the rise of negative dispersion for slow axis was stopped and started to fall eventually after exceeding the wavelength of 1.55μm. We measured the dispersion to be -1449 and -1314 ps/(nm.km) for slow and fast axis respectively when the operating wavelength was set to 1.55μm and the value of pitch Λ was set to 0.77μm.

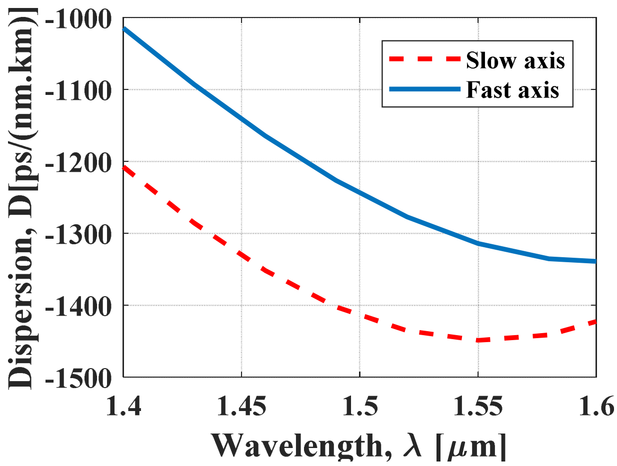


Fig. 3. Dispersion with respect to wavelength for fast and slow axis with pitch = 0.77μm, $d_1/\Lambda$=0.73, $d_2/\Lambda$ = 0.25.

The relationship between dispersion and wavelength at different pitch-values was analyzed and the result was presented in Fig. 4. We studied the change of dispersion and measured their values at 1.55μm. The dispersion was observed to be -1307, 1391 and 1449 ps/ (nm.km) for three different pitch values of 0.81μm, 0.79μm and 0.77μm, respectively. Thus, the negative dispersion level was found higher for lower pitch value.

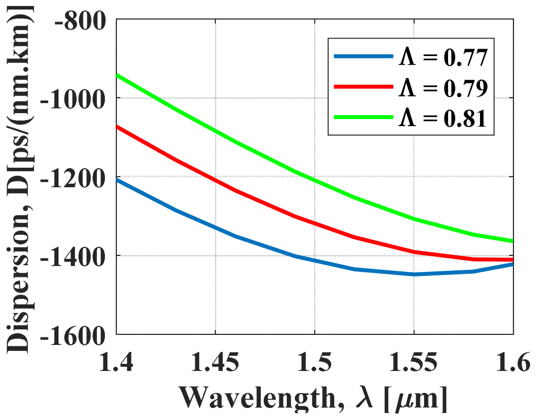


Fig. 4. Dispersion versus wavelength for different pitch values.

Now dispersion of the designed PCF can also be affected by the change of $d_1/\Lambda$. The effect of changing $d_1/\Lambda$ on dispersion was tested and the result is shown in Fig. 5. We measured the dispersion to be -1307, -1449 and -1554 ps/ (nm.km) for the $d_1/\Lambda$ values of 0.75, 0.73 and 0.70μm respectively at 1.55μm wavelength. So, the negative dispersion is observed to be increased with the decrease of $d_1/\Lambda$.

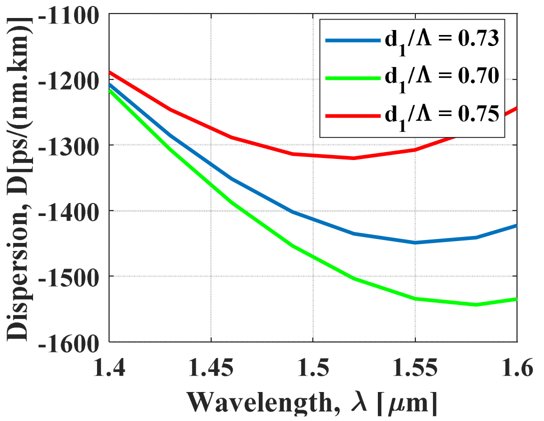


Fig. 5. Dispersion to the O-PCF for $d_1/\Lambda$ =0.73, 0.70 and 0.75.

Similarly, the effect of changing $d_2/\Lambda$ values on dispersion is also investigated and the graphical representation is given in Fig. 6. We measured the dispersion to be -1408, -1449 and -1489 ps/(nm.km) for the diameter values of 0.23, 0.25 and 0.27μm respectively at 1.55μm wavelength. So, the negative dispersion is found to be increased with the increase of $d_2/\Lambda$.

Fig. 7 shows the change of dispersion due to the change of air-hole diameter $d_1/\Lambda$ in the tolerance range of ±2 present. We observed the dispersion to be -1323, -1386, -1511 and -1574 ps/(nm.km) for the tolerance level of -2%, -1%, 1% and 2%, respectively. The calculated dispersion is -1449 ps/ (nm.km) due to the optimum value of $d_1/\Lambda$ which is considered to be 0.73μm.

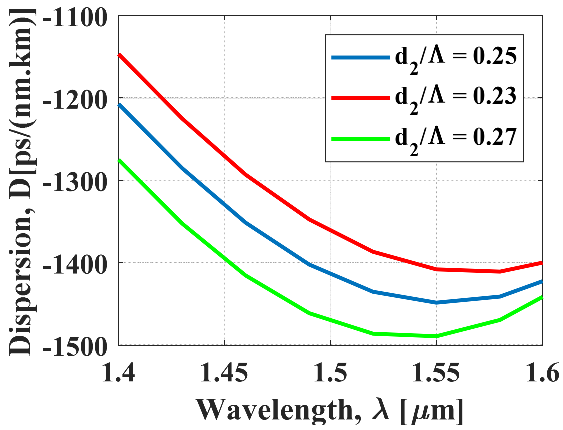


Fig. 6. Dispersion properties for different values of $d_2/\Lambda$ = 0.23, 0.25, 0.27.

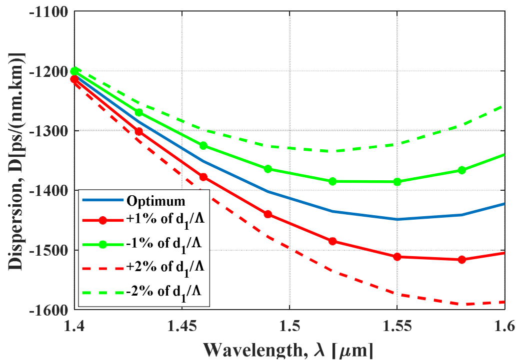


Fig. 7. Wavelength dependent dispersion properties for $d_1/\Lambda$ tolerance range of ±2%.

Similarly, the change of dispersion for changing diameter $d_2/\Lambda$ in the tolerance range of ±2% is shown in Fig. 8. We observed the dispersion to be -1428, -1438, -1459 and -1469 ps/ (nm.km) for the tolerance level of -2%, -1%, 1% and 2%, respectively at 1.55μm. The obtained dispersion is -1449 ps/ (nm.km).

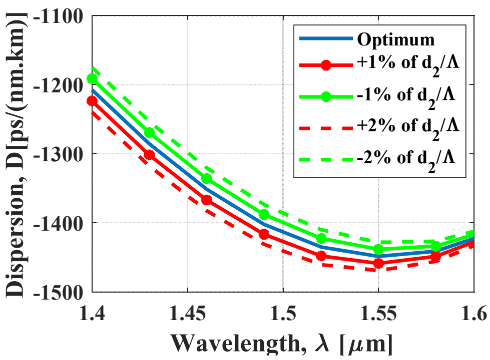


Fig. 8. Wavelength dependent dispersion properties for $d_2/\Lambda$ tolerance range of ±2%.

Then we observed the effect of changing pitch in the tolerance range of ±2% on dispersion and the result is shown in Fig. 9. We found the dispersion to be -1365, -1407, -1490 and -1532 ps/ (nm.km) for the tolerance level of -2%, -1%, 1% and 2%, respectively at 1.55μm.

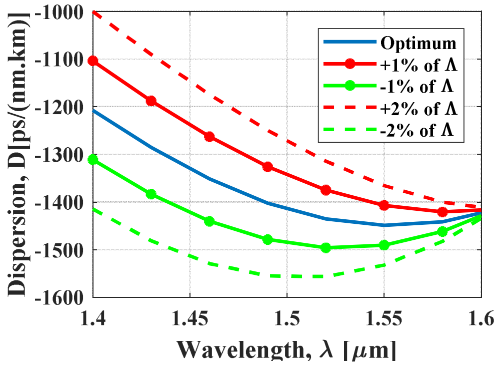


Fig. 9 Wavelength dependent dispersion properties for pitch tolerance range of ±2%.

Furthermore, we observed the change of nonlinear co-efficient of the proposed PCF for changing the value of $d_1/\Lambda$. At excitation wavelength of 1.55µm, the nonlinearity range was in between 106.3 $W^{-1}km^{-1}$ and 95.29 $W^{-1}km^{-1}$ for ±2% tolerance range. For the optimum value of $d_1/\Lambda$, the nonlinearity was 100.5 $W^{-1}km^{-1}$ at 1.55µm wavelength.

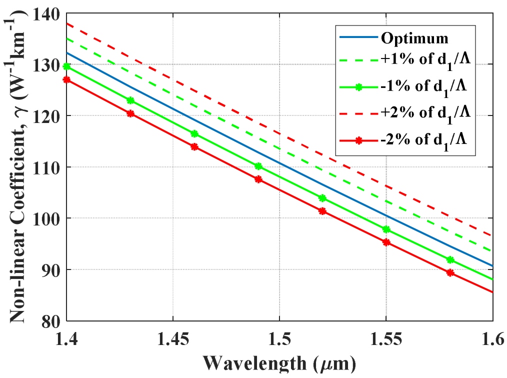


Fig. 10. Nonlinearity with respect to wavelength for $d_1/\Lambda$ tolerance range of ±2%.

Similarly, Fig. 11 represents the relationship between nonlinearity and $d_2/\Lambda$. We found that the change of $d_2/\Lambda$ in ±2% tolerance range barely changed the value of nonlinearity and its value was found to be fixed at 100.5 $W^{-1}km^{-1}$ at the wavelength of 1.55µm.

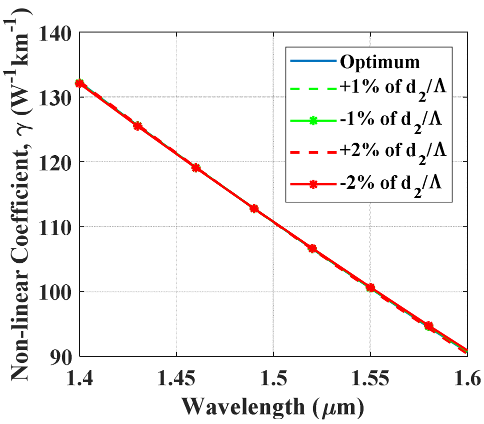


Fig. 11. Nonlinearity with respect to wavelength for $d_2/\Lambda$ tolerance range of ±2%.

Finally, the change of nonlinearity of the proposed PCF with respect to pitch was observed which is shown in Fig. 12. The nonlinearity due to positive percentage of pitch started to decrease with the increase of wavelength, but nonlinearity due negative percentage of pitch started to increase. All values of nonlinearly was equal to the optimum magnitude of 100.5$W^{-1}km^{-1}$ at 1550 nm.

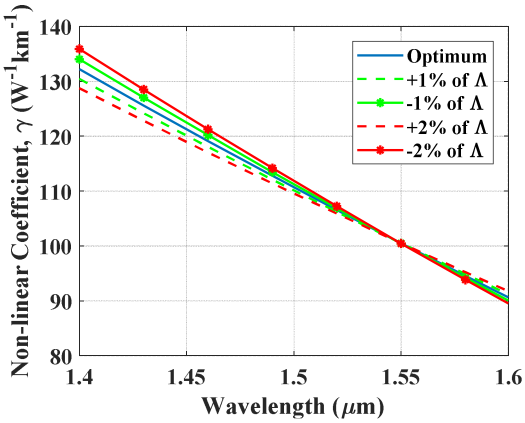


Fig. 12. Nonlinearity with respect to wavelength for pitch tolerance range of ±2%.

Finally, we compare the modal optical properties of designed O-PCF with the other recent works in Table 1. These optical characteristics include dispersion and nonlinear co-efficient which are all measured at 1.55µm wavelength. Table 1 shows that the proposed PCF has the highest nonlinearity compared to other PCF structures. Its dispersion is almost 2 times larger than the other structures except Ref. [18] which has achieved higher negative dispersion by using non-circular air-holes. But using two different types of air-holes accelerates the fabrication complexity as well as the overall cost of manufacturing which is not desired. Therefore we used only circular shapes for the proposed PCF and tried to achieve as high negative dispersion and nonlinearity keeping the structural design as well as fabrication process as simple as possible. The proposed O-PCF plays an important role for the application in an ideal optical back propagation [19]. Ideal optical back propagation is highly depending on high negative dispersion and non-linear co-efficient.

TABLE I. COMPARISON OF THE MODAL PROPERTIES OF O-PCF DESIGN WITH OTHER RECENT PCF DESIGNS AT 1.55µM.

| **Ref. No.** | ***D(λ)* [ps/(nm.km)]** | ***γ* ($W^{-1}km^{-1}$)** | **Air-Hole nature** |
|---|---|---|---|
| [14] | --- | 68.00 | Circular |
| [15] | −578.50 | 53.10 | Circular |
| [16] | -544.70 | 52.7 | Circular and Elliptical |
| [17] | -650.00 | 45.50 | Circular |
| [18] | −1694.80 | 92.83 | Circular and Elliptical |
| Proposed PCF | -1449 | 100.5 | Circular |

## V. CONCLUSION

In this work, we presented a novel design of octagonal lattice PCF that shows a large dispersion with high nonlinearity for broadband dispersion compensation. It has been shown from simulation results that by using the proposed PCF, negative dispersion of -1449 ps/(nm.km) and nonlinearity of 100.5 $W^{-1}km^{-1}$ at 1550 nm wavelength is possible to achieve. The exhibition of large dispersion and high nonlinearity over contemporary PCF designs make it a suitable candidate for high speed optical broadband communication, super continuum generation, and optical amplification. Moreover, the proposed PCF is comparatively easy to fabricate due to its modest number of design parameters.

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