Analysis of Microstructured Photonic Crystal Fiber: An Improved Design

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***Abstract*— A single-mode defected core hexagonal photonic crystal fiber (H-PCF) is presented for the wide-band dispersion compensation at the wavelength interval 1350 to 1600 nm over the telecommunication windows. Finite element method (FEM) is incorporate to investigate the characteristics of the proposed PCF. Throughout the simulation, we found dispersion of -2160 ps.nm^{-1}.km^{-1} and high nonlinearity of 120 W^{-1}km^{-1} at the operating wavelength of 1550 nm. Our proposed paper enhances its attraction for using single circular hole of air in the core site which is the most suitable one for the optical fiber communication systems.**

Keywords*— *Nonlinearity, Photonic crystal fiber, Dispersion.

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]. Moreover, it is extensively used for both telecom applications and in non-telecom systems on account of its small size, higher bandwidth, longer repeater span, electromagnetic immunity, formation of air hole's structure and many other challenging properties [2].

In modern era, photonic crystal fiber (PCF) has performed important role to exhibit the optical properties such as nonlinearity, dispersion, confinement loss as well as simple to fabricate using current fabrication technology. But constructing PCF can be done since all air holes are circular. This method is called drilling, stack or drew method. By this method, Yang et al. reported a PCF with birefringence of 2.2 × 10^{-2}, nonlinearity of 68 W^{-1}·km^{-1}, and confinement loss of 10^{-4}dB/m [3]. High Nonlinearity and high dispersion are a great concern for fiber optic transmission system. For this, Lee et al. have designed a novel square geometry structure that consists twenty-four smaller shaped circular air holes at the center and found dispersion of −150 ps/(nm.km) at working wavelength of 1550nm [4].

In practical operation, we need higher negative dispersion, higher nonlinearity, low confinement loss. Using single-mode photonic crystal fibers (SMPCFs) parameters we can enhance high negative dispersion where maintaining the PCF air-hole size. In this process [5] Prajapati et al. proposed highly negative dispersion compensating modified photonic crystal fiber for wavelengths ranging from 1200 to 2500 nm covering more than E-S-C-L bands.

Recently, we have developed a novel photonic crystal fiber to study the impact of geometric parameters on fiber dispersion and nonlinearity [6]. This designed provide dispersion of−2102 ps/(nm km), and nonlinearity of 120 W^{-1} km^{-1} by omitting a single air hole at the core region. Dispersion is a big problem for wavelength division multiplexing (WDM) as well as high speed propagation because of widen the optical pulse along with reduced the bandwidth of this system.

However, to mark up the transmission technology we proposed micro structured photonic crystal fiber in shape of hexagon in the fiber lattice. Our proposed design offers large nonlinear coefficient which is 120 W^{-1} km^{-1} as well as dispersion about -2160 ps/(nm.km) at 1.55μm which can be the most hopeful applications of super-continuum generation (SCG). In addition, our designed H-PCF also better for its design simplicity. Consequently, it is expected that for its high dispersion with high nonlinearity would be the most auspicious for efficient dispersion compensation application. The novelity of the proposed PCF is arise due to use of smaller air holes of diameter $d_3/\Lambda = 0.19$ inside the first ring. This air hole significantly alters the refractive index profile of the proposed PCF which leads to enhance optical properties such as dispersion and nonlinearity.

II. Geometric structure

In Figure 1, the arrangement of airholes of the proposed PCF is shown. This proposal consists only silica material as silica has a powerful impact on dispersion feature [3-6]. To make the most feasible fabrication process and for obtaining large nonlinear property only one circular air hole is used inside core in the designed H-PCF.

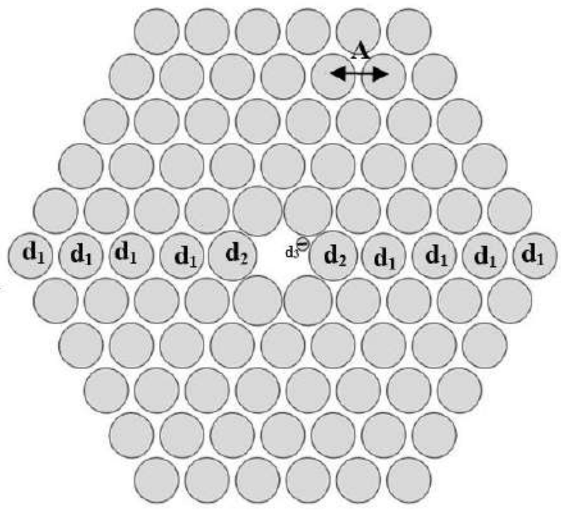


Fig. 1. Transverse cross-sectional view of proposed H-PCF.

Three types of air holes whose diameter (d_1, d_2 and d_3) are used to design the lattice. Among them d_1 and d_2 are the largest diameter and d_3 is the smallest one. The Centrum to Centrum difference between the nearest two air holes as displayed in figure 1 is called pitch which is consoled by Λ. In this way, the proposed H-PCF displays four geometrical parameters (d_1,

d_2, d_3 and Λ) which can be chosen as degrees of freedom. Optimum characteristics of the proposed PCF such as high negative dispersion coefficient, high nonlinearity can be found by tailoring the geometric parameters (d_1, d_2, d_3 and Λ).

III. NUMERICAL METHODS

Finite Element Method (FEM) software & COMSOL Multi-physics for full vector has been used to handle the proposed H-PCF model analysis and its simulation. The propagation characteristics are obtained from Maxwell's equations.

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

Here, D (λ) indicate the chromatic dispersion; Re (n_{eff}) indicate the actual-part; c indicates the light-velocity and λ indicate the wavelength.

The birefringence (B) can be estimated from the following formula

$$B = |\, n_x - n_y \,|$$

Here, B indicates birefringence; n_x and n_y indicates effective refractive index in X and Y polarization, respectively.

Nonlinear coefficient can be represented by the pursuing equations

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

Kerr constant is represented by n_2

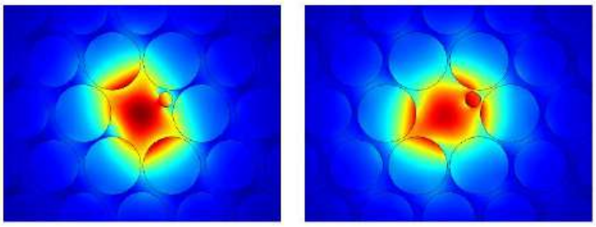
Aeff is called effective mode area and can be represent as

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

where E denotes electric field intensity. Smaller effective mode area leads higher nonlinearity.

IV. RESULTS ANALYSIS

Figure 2 shows the optical field patterns of designed PCF. Here operating wavelength is 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. Fig 3 shows dispersion characteristics of the mentioned H-PCF for both axis using pitch Λ=0.76 μm. From the graph, it is noticed that y polarized mode shows dispersion of -2160 ps/(nm.km) at 1.55μm wavelength.



(a) (b)

Fig. 2 Optical light confinement: (a) fast and (b) slow axis

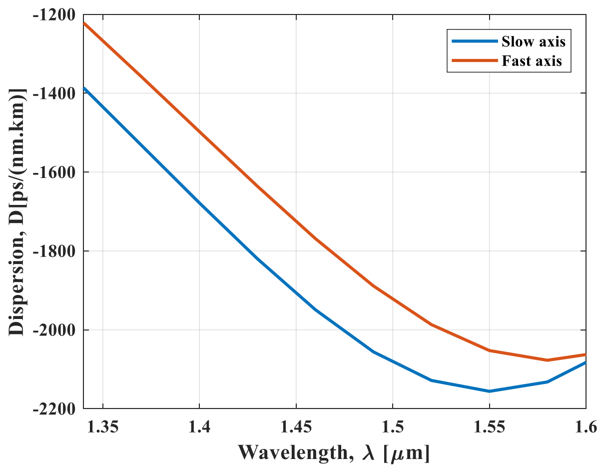


Fig 3: Dispersion characteristics as a function of wavelength.

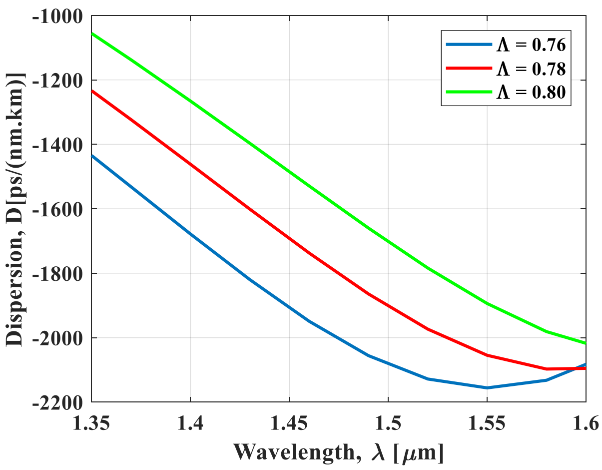


Fig 4 Dispersion versus wavelength of the H-PCF due to different values of pitch Λ.

Fig 4 allows to understand how the dispersion properties of hexagonal-lattice PCFs change as a function of pitch Λ. Here pitch value changes from 0.76 μm to 0.80 μm. It can be observed that the dispersion characteristics of the designed PCF are greatly influenced by the pitch. Smaller value of pitch provides better results as compared with large value. As pitch is changed from 0.76 to 0.80, the distance between the center of 2 neighboring airholes are increased and hence, dispersion decreases.

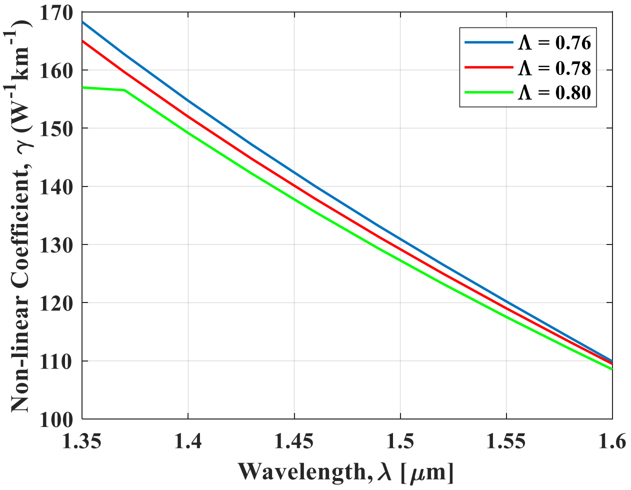


Fig 5: Effect of changing pitch on nonlinear coefficient.

In Fig 5, the nonlinear coefficient is plotted against wavelength where pitch Λ is varied but diameters of the air holes keep constant. Here the nonlinear co-efficient is about 120 $w^{-1}km^{-1}$ at operating wavelength of 1.55 µm when pitch Λ is 0.76. Fig 6 represents of the effect on varying pitch of the dispersion characteristics from ±1% to ± 2 %. At 1.55 µm, the availed result for ± 1% of pitch is -2110 and -2160 ps/(nm.km), respectively.

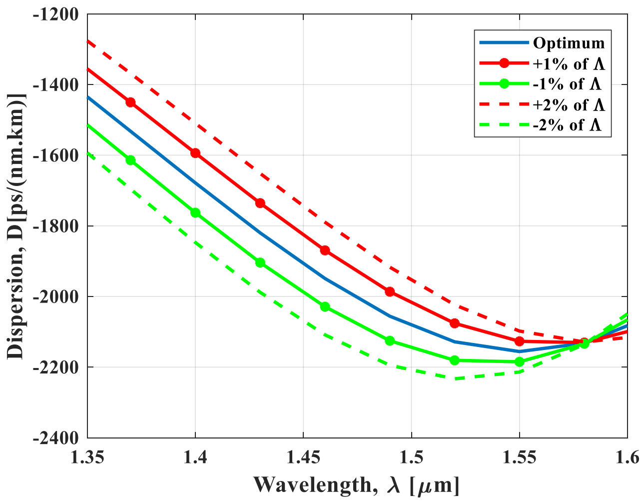


Fig 6: Fabrication anaysis by varying the pitch from ± 1% to ± 2 %.

Fig 7 displays the impact of varying d_1/Λ on dispersion properties when Λ = 0.76 and d_2/Λ = 0.96 are fixed. At, λ = 1.55 µm dispersion features are -2160,-1900,-1680 ps/(nm. km) respectively d_1/Λ was shifted to 0.87, 0.89, and 0.91. From figure 7 it can be seen that when Λ and d_2/Λ are fixed but d_1/Λ shifting it can influence dispersion feature.

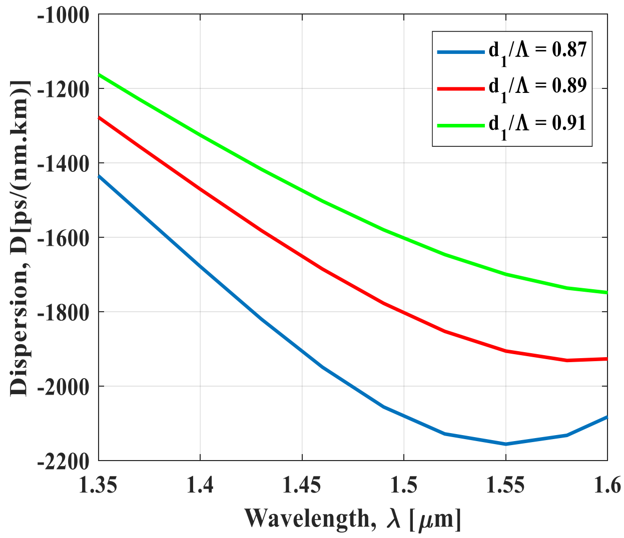


Fig 7: Dispersion versus wavelength where d_1/Λ = 0.87, 0.89 and 0.91.

Fig 8 displays the dispersion characteristics on changing d_2/Λ from 0.92 to 0.96. At, λ = 1.55 µm dispersion features are -2160 ,-1850,-1600 ps/(nm km) respectively,when d_2/Λ is shifted to 0.96, 0.94, and 0.92.

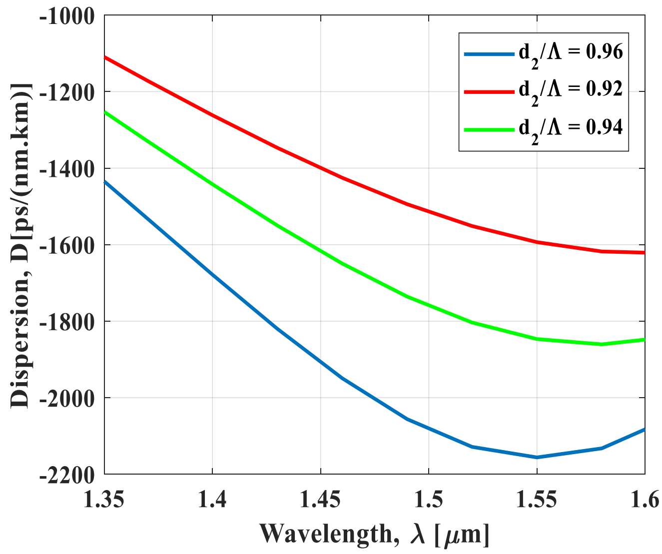


Fig 8: Dispersion versus wavelength where d_2/Λ = 0.96, 0.92 and 0.94.

Fig 9 reveals the impact of dispersion properties on d_3/Λ when d_1/Λ = 0.87 as well as d_2/Λ=0.96 are fixed. The values for d_3 are chosen as 0.19, 0.17, 0.15 and the respective dispersion is -2160, -2118, and -2088 ps/(nm.km) at operating wavelength of 1.55 µm.

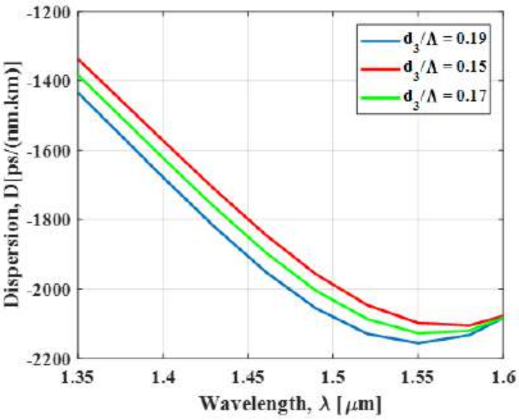


Fig 9: Dispersion versus wavelength where d_3/Λ = 0.19, 0.15 and 0.17.

Fig 10 shows the effect of non linear co-efficient against wavelength when pitch Λ and diameter d_2, d_3 are fixed when d_1/Λ is varied from 0.87 to 0.91 ,the result is also varied from 120 $w^{-1}km^{-1}$ to 118 $w^{-1}km^{-1}$ at 1.55 µm.

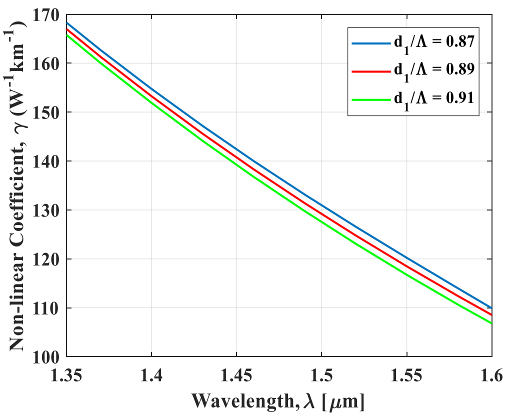


Fig 10: Non linear coefficient versus wavelength where d_1/Λ = 0.87, 0.89 and 0.91.

TABLE I. COMPARISON OF DISPERSION AND NONLINEAR PROPERTIES WITH RECENT PCFS.

Reference	**Dispersion,**	***Nonlinearity***	**Air-hole shape**
[3]	---	68	Circular
[4]	-150	---	Circular
[5]	-722.48	---	Square
[6]	−2102	111.6	Circular
Proposed PCF	-2160	120	Circular

Finally, in table 1, a comparativ analsis has been done by taking into account dispersion and nonlinear properties of the proposed PCF. After exploration it is seen that our proposed PCF design is far better than other designs. Our design is better because it has large negative dispersion and nonlinear co-efficient while using same shape of air hole compared with [6]. After comapring, it is noticed that we found 14.4, 2.99, 1.03 times higher negative dispersion comapre to [4], [5], [6], respectively and 1.76, 1.07, times higher non linear coefficient with comapre to [3], [6], respectively. Again fabrication is more robust and feasible with compare to others as well as it offers additional efficiency. Our proposed design can be used in high-speed transmission system for broadband dispersion compensation over longer distance, nonlinear optics and sensing applications as well [7-11].

V. CONCLUSION

In conclusion, A H-PCF model is designed and analyzed as a highly negative dispersion compensating fiber. This proposed microstructure is able to demonstrate large dispersion of -2160 ps/(nm.km) and nonlinearity of 120 $W^{-1}km^{-1}$ at the excitation wavelength of 1550nm. The fabrication technique for the designed PCF is also discussed. The proposed PCF can be used in fiber optic transmission system to compensate dispersion over long distance.

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