Highly Birefringent Dispersion Compensating Index Guiding Square Photonic Crystal Fiber with Large Nonlinearity for Fiber Optic Transmission System

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***Abstract*— A square lattice dispersion compensating highly non-linear photonic crystal fiber is presented in this paper. Finite Element Method (FEM) with the perfectly matched layer is used to observe the impact of fiber parameters on birefringence, dispersion, and nonlinearity. The proposed highly birefringent dispersion compensating fiber shows that it is possible to obtain birefringence of 3.2×10^{-2} and dispersion of -1501 ps/(nm.km) at 1550nm wavelength by adopting the smallest number of design parameters. The proposed fiber will be an excellent candidate for dispersion compensation in fiber optic transmission system.**

Keywords—Birefringent, S-PCF, Dispersion

I. Introduction

Photonic crystal fiber (PCF) plays an important role in modern telecommunication systems. In recent years photonic crystal fiber provides numerous novel designs which are used in telecommunication systems, sensor technologies, and spectroscopy [1]. Photonic crystal fiber illustrates that it is modernistic optical fiber which has tremendous optical properties such as birefringence, dispersion, non-linearity, effective area etc. These properties make photonic crystal fiber not only stronger but also more reliable than conventional optical fibers. According to guiding mechanisms PCF can be classified into two different types such as index-guiding PCF where light lead by internal reflection and another one is photonic band gap fiber. Index-guiding PCFs contain a solid core, where wave guiding occurs due to total internal reflection akin to conventional fibers. However, in hollow-core PCFs, the core consists of a hollow air hole to utilize the photonic band gap of the cladding region for wave guiding. PCFs are recently seen as a promising technology to replace conventional optical fibers in communication, laser and sensor applications due to their design flexibility. PCFs allow control of optical properties and confinement characteristics of the material by manipulating the lattice pitch, air hole shape and diameter, refractive index of the glass, and type of lattice [2]. This, in turn, affects the modal properties of PCFs such as chromatic dispersion, effective mode area, confinement loss, birefringence and nonlinear coefficient. In this paper, we discuss a square lattice to gain high negative dispersion and ultra-high birefringence. Square lattice is preferable over a triangular lattice because it has tremendous properties. Square lattice PCF needed an immensely effective area which has better power management rather than triangular lattice PCF.

Another most encouraging application arise of PCFs is an improvement of high birefringence along with nonlinearity. The nonlinear PCFs properties grant new light sources with very ample spectra which is already proven. To transmit data over long distance accurately high negative dispersion coefficient along with high birefringence is very important. In addition to, nonlinearity is very much useful for the application of super continuum generation [3].

Recently a large number of PCF designs have been proposed and investigated to attain high nonlinearity along with broadband dispersion compensation. To compensate chromatic dispersion a single mode circular PCF is designed by Haque *et al*, which provide large dispersion peak of -386.57 to -971.44 ps/(nm.km) at the wavelength range from 1340 to 1640nm [4]. Hasan et al. has designed a hybrid PCF structure with hexagonal and decagonal cladding rings and reported dispersion coefficient of −242.22 to −762.6 ps/(nm.km) [5]. Wang *et al.* have reported negative dispersion properties using their hybrid design with rectangular holes arranged as triangular and rectangular lattices in the fiber core [6]. Dispersion coefficient of -1320 ps/(nm.km) has been reported by Chen *et al.* using circular air holes arranged in a honeycomb pattern in the PCF cladding [7]. However, fabrication of the fiber is the main challenge in the above-mentioned PCF designs.

In this paper we have designed and proposed simple square-based PCF which exhibits a highly negative dispersion coefficient of -1501 ps/(nm.km), nonlinear co efficient of 91.28 $W^{-1}km^{-1}$ and ultra-high birefringence of about 3.2×10^{-2} at 1.55μm wavelength. To characterize the various light guiding properties COMSOL Multiphysics is used as a simulation tool.

II. Geometric Structure and Numerical Method

Fig. 1 shows the proposed PCF geometry and arrangement of the air holes in the silica cladding. The structure is a conventional square lattice consisting of five air hole rings and a solid core. Silica containing strong and high impact on the PCF dispersion properties, so silica is chosen as background material for this proposed design. To make the fabrication system easier and more reliable any non- circular air holes such as elliptically shaped holes or rectangular air holes is not introduced in this paper, only circular air holes are used in this design. In this proposed design the square lattice PCF contains five rings of air holes which have equal diameter d_1. Two smaller air holes are placed between the large air holes and the diameter of these two air holes are denoted by d_2. Pitch plays an important role in design of any PCF. The distance between one air hole to another air hole is known as pitch which is also denoted by Λ.

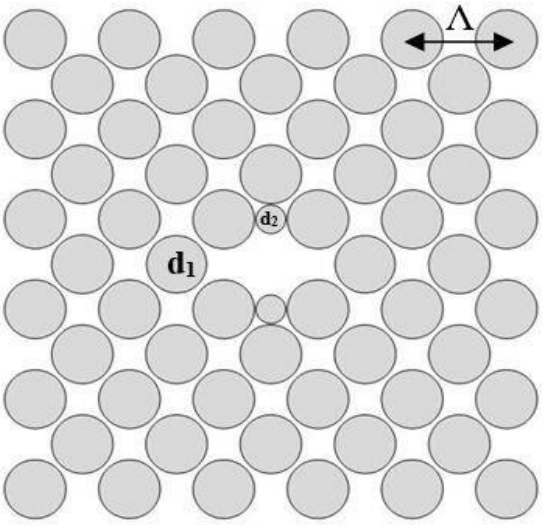

Fig. 1. Cross-section of the proposed S-PCF.

To investigate the result of the guiding properties of proposed PCF, the Finite Element Method (FEM) has been used with circular perfectly matched layer boundary. Comsol Multiphysics 4.2 is used to investigate the impact of fiber parameters of the proposed fiber. Comsol generally was widely known as a commercially available full vector FEM software. As the background of the proposed design is silica hence the refractive index is calculated through Sellmeier's equation which is given by

$$n(\lambda) = \sqrt{1 + \frac{B_1\lambda^2}{\lambda^2 - C_1} + \frac{B_2\lambda^2}{\lambda^2 - C_2} + \frac{B_3\lambda^2}{\lambda^2 - C_3}}$$

Chromatic dispersion is calculated from the fundamental mode of effective index and wavelength.

Chromatic Dispersion,

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

Here, wavelength=λ, velocity of light in vacuum =c, real part of effective index=Re $[n_{eff}]$. The modal effective index n_{eff} is depended on ($n_m(\lambda)$) and denoted as

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

k_0 is denoted by 2π/λ which is the wave number of free spaces, β is the propagation constant.

$$B = \left|n_x - n_y\right|$$

By using this equation, the birefringence B is obtained where n_x and n_y are the representation of the effective refractive index for both x and y polarization respectively.

The non-linear coefficient γ is indicated by using the equation is given below

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

Nonlinearity is an important parameter to investigate the nonlinear effect of optical micro cavity. The nonlinear coefficient (γ) is inversely proportional to the effective mode area A_{eff} which is denoted by

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

III. DISPERSION ANALYSIS OF THE STRUCTURE

Fig. 3 illustrate the dispersion values of proposed S-PCF. By using an optimal pitch Λ = 0.76, the designed PCF exhibits a high value of dispersion of -1501 ps/(nm.km) for slow axis and -925.8 ps/(nm.km) for the fast axis at a wavelength of 1550 micro meter. The magnitude of the slow axis is almost 1.05 times larger than that of fast axis. On the other hand, the constructed fiber shows an incredibly immense negative dispersion coefficient range of around −1200 to −1508 ps/(nm.km) over 1350 - 1600 micro meter wavelength band for the optimum value of the designed parameters. Highly negative dispersion is a crucial parameter for constructing the fiber which has to be as huge as feasible in particular to trim the length of dispersion compensating fiber.

Now, in Fig. 4 demonstrate the calculation of pitch variation where d_1 = 0.70μm, d_2 =0.34μm are kept constant. The pitch variation is chosen as Λ=0.76, 0.78 and 0.80. At operating wavelength of 1.55μm, the results are -1501, -1385 and -1262 ps/(nm.km), respectively. From Fig. 4 it can also clearly observed that pitch is inversely related to negative dispersion. Hasan et.al showed that PCF can provide 100 times better dispersion than ordinary optical fiber [7].

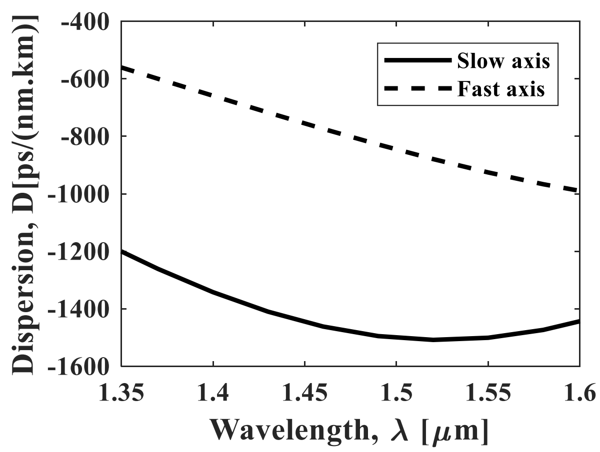

Fig. 3. Dispersion as a function of wavelength for fast axis and slow axis using Λ = 0.76 μm and d_1 =0.7μm, d_2 =0.34μm.

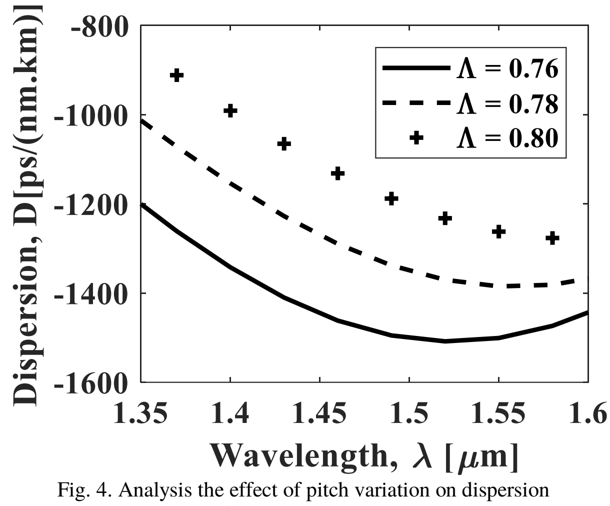

Fig. 4. Analysis the effect of pitch variation on dispersion characteristics.

To investigate the diameter variation of d_1 of the proposed S-PCF we changed diameter d_1 values from 0.66μm to 0.70μm where Λ and d_2 are kept constant in Fig. 5. Now the calculated values are -1501, -1435 and -1369 ps/(nm.km), respectively at 1.55μm. It also shows that dispersion variation is proportionally related with diameter d_1.

Fig. 6 shows the effects of diameter d_2 variation on fiber dispersion behavior by keeping d_1, and pitch Λ constant. The values for d_2 are chosen as 0.34, 0.32 and 0.30 for which the obtained result is -1501 ps/(nm.km), -1420 ps/(nm.km), -1339ps/(nm.km), respectively at excitation wavelength of 1550 nm.

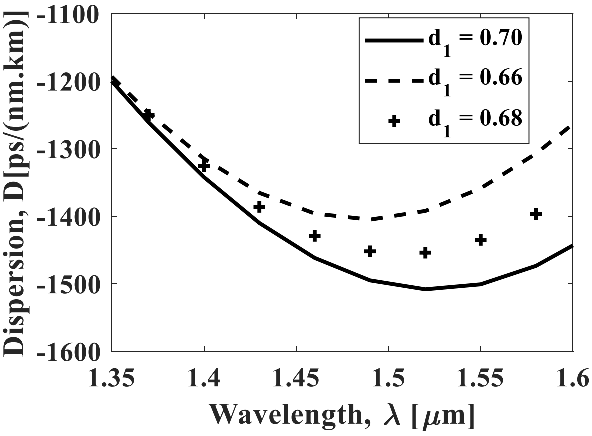

Fig. 5. Analysis the effect of diameter d_1 variation on dispersion characteristics.

In Fig 7 shows the dispersion characteristics by varying the d_1 parameter from ±1% to ± 2 %. For ±1% the dispersion vs wavelength curves demonstrate that for +1% the result is -1523 ps/(nm.km) and for -1% the result is -1478 ps/(nm.km) and for ± 2% it shows that the result is -1478 ps/(nm.km) and -1546 ps/(nm.km) at operating wavelength of 1550nm. The average optimum value for ±1% and ±2% is exactly -1501 ps/(nm.km) at 1550 nm wavelength.

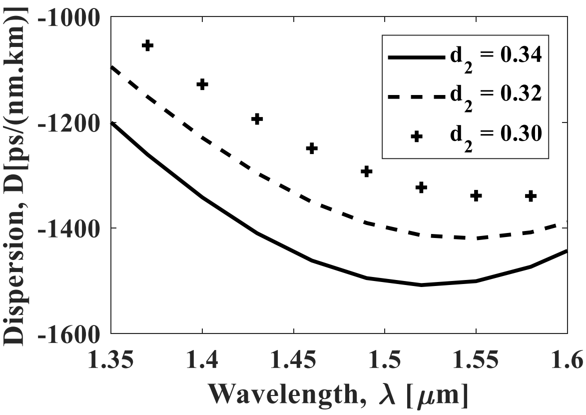

Fig. 6. Analysis the effect of diameter d_2 variation on dispersion characteristics.

Figure 8 represents an illustration of the effect on varying pitch of the dispersion characteristics from ±1% to ± 2 %. The obtained result for ± 1% of the pitch is -1459 and -1543 ps/(nm.km) respectively and for ± 2% of pitch, the result is -1417 and -1585 ps/(nm.km) respectively at 1.55μm. The average optimum value for pitch is -1501 ps/(nm.km) at 1550 nm wavelength.

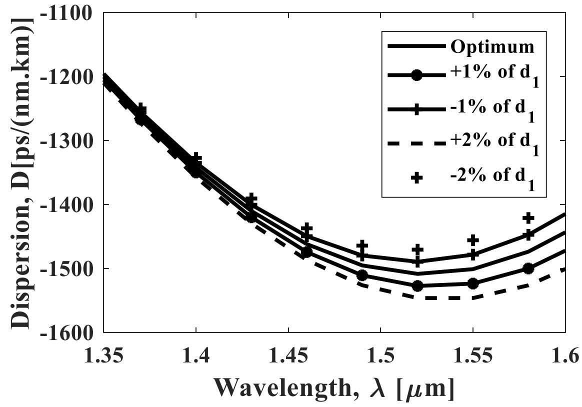

Fig. 7. Analysis the diameter tolerance on dispersion characteristics.

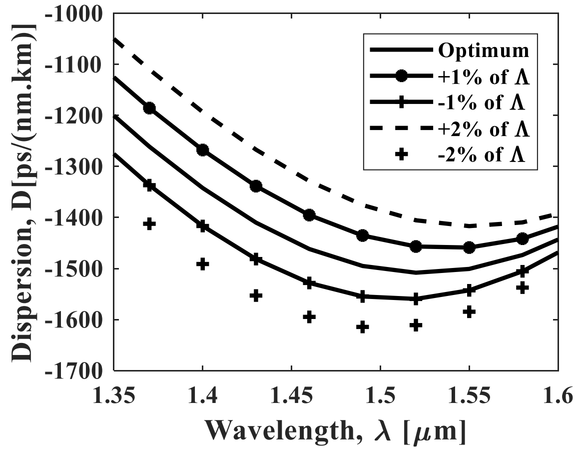

Fig. 8. Analysis the pitch tolerance on dispersion characteristics.

IV. BIREFRINGENCE ANALYSIS OF THE STRUCTURE

Fig. 9 shows the effect on the birefringence properties due to the variation of adjacent airhole spacing. From the figure, it is observed that high birefringence is obtained when adjacent air hole spacing decreases -2%. The deviation of air hole spacing is considered to justify the fabrication tolerance. The optimum value of modal birefringence is 0.032. From Fig. 9 it can also be seen that birefringence values significantly change due to the fluctuations of global design parameters for the proposed S-PCF. Therefore, from the above investigation it is clearly evident that the tolerance of the optical birefringence of the proposed PCF can be controlled by maintaining a proper precision of pitch during fabrication process. Habib et al. already proved that highly birefringent fiber with negative dispersion is highly suitable for optical amplification applications.

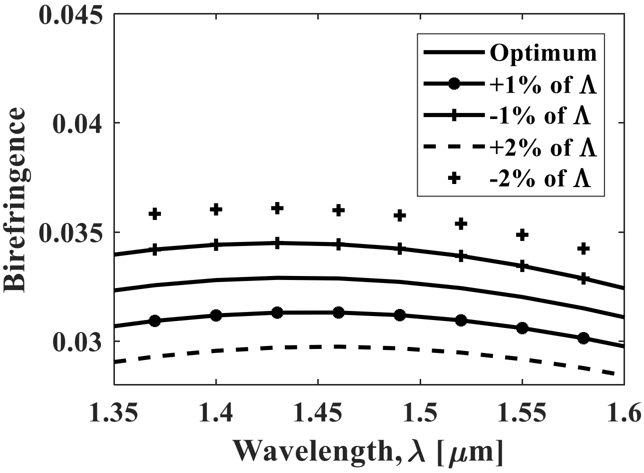

Fig. 9. Analysis the effect of birefringence on pitch tolerance from ±1% to ± 2 %.

V. Nonlinearity Analysis of the Structure

The novelity of the proposed S-PCF is arise due to use of two smaller air holes of diameter d_2 inside the first ring. These two air holes significantly alters the refractive index profile of the proposed S-PCF which leads to enhance optical properties such as nonlinearity. Figure 10 is clearly showing the relation of the non-linear coefficient with wavelength. From the figure, it is also clearly found that the non-linear coefficient is reverse compared to effective area. That means non-linear coefficient is decreasing according to the increases of wavelength. The nonlinear coefficient is about 91.28 $W^{-1}km^{-1}$ at operating wavelength of 1550nm.

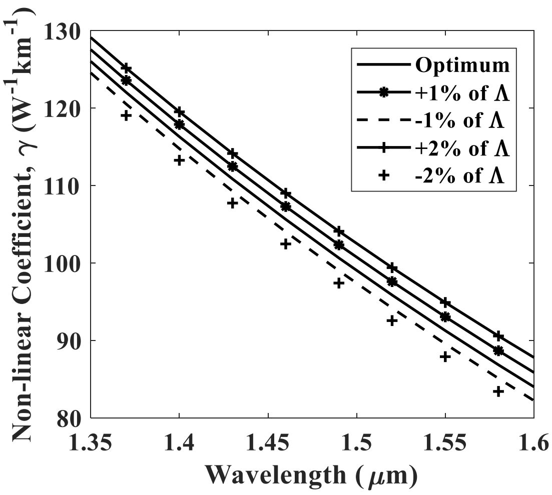

Fig. 10. Effect of changing pitch on nonlinear coefficient.

VI. Comparative Analysis

Table. 1 compare he modal properties of the proposed S-PCF in terms of dispersion, birefringence, and non-linear coefficient at operating wavelength of 1550 nm. From the table, it indicates that the proposed S-PCF design gained excellent result for dispersion, birefringence and non-linear coefficient. From the table, it can be concluded that the negative dispersion of the proposed PCF is very high than Ref. [5, 8-11]. The dispersion of the proposed PCF is 2.59, 1.42, 2.30, 2.44, 1.21 times higher than [5, 8-11], respectively. In addition, the designed square PCF exhibits high birefringence of 3.2×10^{-2} which is higher than all the other references except [8]. But the nonlinearity of the proposed PCF is two times and dispersion are 1.42 times higher than the Ref. [8]. The nonlinear coefficient is higher than [5, 8-11] which is 91.28 $W^{-1}km^{-1}$. So, all the properties of the proposed S-PCF are highly suitable for optical communication.

Table 1: A comparison table on the contemporary PCF structures with the proposed S-PCF at 1550 nm wavelength.

PCFs	D (λ) ps. nm^{-1} km^{-1}	B=$\|n_x$-$n_y\|$	γ (W^{-1} km^{-1})
[5]	-578.5	2.64×10^{-2}	53.10
[8]	-1054.4	3.45×10^{-2}	39
[9]	-650.0	2.10×10^{-2}	45.50
[10]	-613.0	2.10×10^{-2}	-------
[11]	-1044	-------	77.85
Proposed PCF	-1501	3.2×10^{-2}	91.28

VII. Fabrication Process of the Proposed S-PCF

To design any PCF structure for attaining maximum utilization of the fabrication process, it is always one of the challenging tasks. But here the fabrication system is comparatively easy as from the Fig. 1 it shows that it made by a square lattice in the cladding which gives extra favor during fabrication. To fabricate any shape of the PCF there are several techniques, but they have some limitations too. The fabrication process of proposed S-PCF may not have unwrinkled due to its large air hole uniformity. The fabrication process complexity may be less according to reference paper. Bise and Trevor have invented a technique named sol-gel can be used to fabricate any PCF structure [12].

VIII. Conclusion

In this article, it has been analyzed and designed a good not only effective but also simple and reliable ultrahigh negative dispersion compensating photonic crystal fiber based on square geometry. Numerical results reveal that it can be possible to obtain high nonlinearity of 91.28 $W^{-1}km^{-1}$, a birefringence of 3.2×10^{-2} and dispersion of -1501 ps/(nm.km) at 1.55μm by adjusting the structural parameters of the proposed S-PCF. The important properties like birefringence, non-linearity, effective area have been observed by using FEM techniques. Because of having good desirable index guiding characteristics, the proposed S-PCF is highly recommended for high-speed reliable transmission system applications.

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