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REGULAR PAPER

Ultra-high negative dispersion compensating square lattice based single mode photonic crystal fiber with high nonlinearity

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Abstract This paper presents dispersion tailoring of photonic crystal fibers creating artificial defect along one of the regular square axes. A finite element method (FEM) has been enforced for numerical investigation of several guiding properties of the PCF covering a broad wavelength range about 1340–1640 nm over the telecommunication windows. According to simulation, the proposed PCF has obtained a strictly single-mode fiber, which has an ultra-high negative dispersion of about −584.60 to −2337.60 ps/(nm-km) and also possible to cover the highest nonlinearity order of 131.91 W^{-1} km^{-1} under the operating wavelength. Moreover, the proposed PCF structure experimentally focuses on higher nonlinear coefficient, which successfully compensates the chromatic dispersion of standard single mode in entire band of interest and greatly applicable to the optical transmission system. Additionally, the single mode behavior of S-PCF is explicated by employing V parameter. In our dispersion sensitive analysis, this fiber is significantly more robust due to successfully achieve ultra-high negative dispersion, which gains more promiscuous compared to the prior best results.

Keywords Ultra-high negative dispersion · Nonlinear coefficient · Dispersion compensating S-PCF · Finite element method · Single mode fiber

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1 Introduction

Now a day, photonic crystal fibers (PCFs) exhibit a broad range of independence to guide the optical characteristics such as birefringence, dispersion, nonlinearity, effective area, endlessly single-mode operation, etc. [1, 2]. Among these dispersions, non-linearity and effective area are the most promising properties to obtain the robust PCF for the high-bit optical transmission system. PCF offers significant variation in tuning dispersion. The dispersion can be considered as a crucial parameter in optical communication that asserts to improve data capacity has been broadly conducted. It spreads out the maximum transmission distance and the bit rate optical pulses when the pulse is being transmitted through the fiber. Hence to reduce the pulse broadening, dispersion must be compensated. According to this reason, dispersion compensation (DC) strategies are an extremely significant issue for fiber optic link. Around the last few years, some DC strategies have been extremely pursued such as dispersion-compensating fiber (DCF) [3], DC gratings [4], electronic DC [5] and optical phase conjugation [6] etc. Due to the manufacturing facilities as well as ease of applications, DCF is the most promising trick that has achieved advanced attention in the research field.

In recent years, Photonic crystal fibers (PCFs) or micro-structured optical fibers (MOFs) have contained various numerous geometries applying the shape, size, pitch and number of air-holes rings around the core and positioning of air-holes in the micro-structured cladding [2, 7]. The flexible geometry of PCFs has not only overcome the limitation of conventional optical fiber but also maintained the light guiding transmission through the fiber. The flexible geometry of PCFs offers a number of unique dispersion properties compared to conventional single modes fibers such as nearly zero ultra-flattened dispersion and high negative chromatic dispersion. Generally, the ultra-low negative dispersion is perused around a narrowband particular wavelength [8–13]. Therefore, our main goal is to achieve high negative dispersion over a spacious wavelength range for the inflictions of broadband dense wavelength division multiplexing (DWDM).

This dispersion compensating fibers (DCFs) follow a rule behind having an ultra-high negative dispersion and being the coupling between two spatially detached asymmetric concentric cores which allow two leaky modes: (1) inner mode and (2) outer mode. Mode matching can occur between these two modes at the expected wavelength by an approximate design. To understand high negative dispersion with triangular lattice PCFs, a few explorations have been executed [11–13]. With the same d/Λ value compared to the triangular one, square-lattice PCF provides a wide range of single mode operation [14]. The effective area of regular square lattice PCF is larger than triangular lattice, thus for high power management square lattice based PCFs are better than triangular lattice PCF [15]. It can be seen that the in-line dispersion around the 1550 nm wavelength can be better compensated by square lattice based PCFs [3] than the triangular-lattice PCF.

At first, Birks et al. [16] had proposed dispersion compensation (DC) PCF which suffers from its short effective area. Then another approach was proposed [10] in which the structured PCF was considered for broadband dispersion compensation with a small dispersion coefficient of approximately −475 ps/ (nm-km). It has high coupling loss with SMF, as well as a small effective area. To overcome those limitations, in the article [11], it has been investigated some approaches with the target of acquiring an ultra-high negative dispersion and an eligible bandwidth for DC. But, highly doped fibers provide large confinement loss as well as fabrication difficulties [17]. In recent year, a PCF has been theoretically proposed by Matsui et al. [18] capable of dispersion compensation over three telecommunications bands together. The drawbacks of this type of structure are low dispersion coefficient [approximately −100 ps/(nm-km)] and it needs to high-bit rate transmission fiber in a long distance to compensate for the collected dispersion.

Recently, in the article [19], it has been represented that all glass (solid) DCFs can acquire a large negative dispersion of approximately −250 to −300 ps/(nm-km). Additionally, traditional DCFs have some drawbacks related to their design [20], materials of diverse thermal expansion coefficients (i.e. silica cladding regions and germanium-doped core). Moreover, several structures for single-material PCFs have been offered to gain a large negative dispersion coefficient, as well as a broad compensation bandwidth (CB) [3]. Those triangular lattice PCFs reflect air-holes including different diameters as well as same air-hole diameter or a dual concentric core. But they have not investigated a negative dispersion coefficient higher than 600 ps/(nm-km) as well as a CB broader than C-band. For a broad compensation bandwidth, as well as high negative dispersion coefficient [−1350 ps/(nm-km)], a honeycomb structure PCF [21] has been offered which contains a Ge-doped central core. The proposed PCF with doped core governs to fabrication difficulties. Recently, in the article [22], the geometrical structure of the proposed PCF which contains the first ring of special 'grapefruit' holes for broadband dispersion compensation.

However, to overcome the above limitations (low dispersion, non-linearity, and effective area) a square lattice photonic crystal fiber (S-PCF) has been offered. In this paper, we have proposed a regular square-lattice PCF which has not only high negative dispersion coefficient of about −1694.80 ps/(nm-km) at the wavelength of 1550 nm but also high non-linearity compared to prior PCF. For certain properties, square lattice based PCFs are more superior to triangular-lattice PCFs [14, 15]. We have successfully investigated tracing the dispersion compensation properties of the S-PCF over wavelength range about 1340–1640 nm. Besides, nonlinearity is one of the most hopeful applications of photonic crystal fibers which have accepted momentous attention in telecommunication and super-continuum generation (SCG) applications. Undoubtedly, our proposed structural PCF will be comprehensively applicable to the optical transmission system.

2 Geometry

Figure 1 shows the cross sectional view of the proposed square lattice PCF (S-PCF) with air hole distribution. For lower refractive index and higher air-filling ratio around the core region, thereby providing strong confinement ability. Adjacent air-holes near to the core are transformed to circular air holes (circle) that have achieved large negative dispersion. It is informed that the dispersion property is affected by the size of the air holes near core [21]. It is also evident that when the elliptical air holes are replaced with several circular air holes near the core, it can be gained better dispersion compensation characteristics. Besides, when applying a traditional PCF topology, it is hard to engineer a large negative dispersion and inspect dispersion slope, high nonlinear coefficient, and polarization-maintaining characteristics simultaneously. Consequently, it is essential to incorporate a design with a large degree of independence regarding the entire geometrical structure parameters. Hence, the proposed structure parameters are namely pitch Λ, air-hole diameters d, d_a and d_b. It can be suitably designed for transmission characteristics such as dispersion, non-linearity and

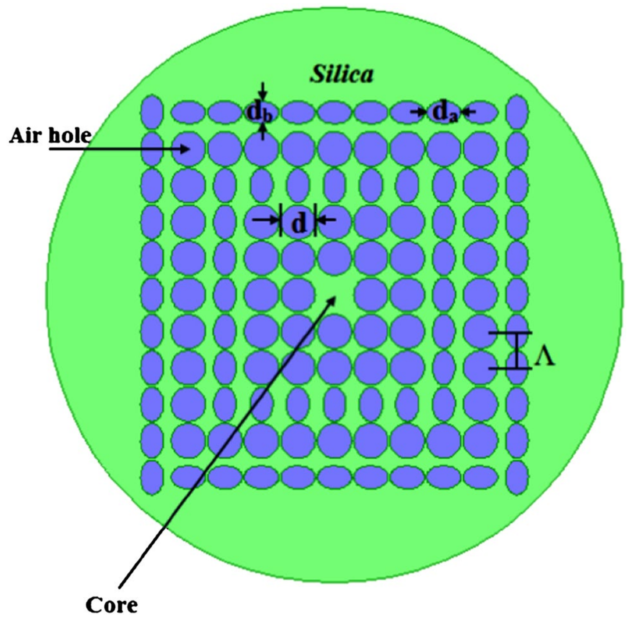

Fig. 1 Transverse cross sectional view of proposed square PCF

effective area which simultaneously acquire a large negative dispersion coefficient, high non-linear coefficient as well as the effective area.

The proposed PCF contains five air hole layers in which three layers (1st, 2nd and 4th) consist of circular air holes and rest of the layers (3rd and 5th) are elliptical air holes. The reason behind replacing circular air holes (3rd and 5th layers) by elliptical air holes is to gain large negative dispersion and high non-linearity. To make the inner core, the central air-hole is missed which forces to achieve high negative dispersion. The proposed PCF consists of 5 rings in which the air holes diameters of three rings (1st, 2nd and 4th) are equal which denoted by d and rest of the elliptical air holes diameters (3rd and 5th layers) are same. The major and minor axes of elliptical air holes are defined as d_a and d_b, respectively. In this case, the square-lattice geometry of the proposed PCF, the hole-to-hole distance both in horizontal and vertical directions [23, 24] is denoted as Λ. The first two air-hole rings have contained with circular rings in inner cladding. Moreover, the 3rd and 5th air-hole rings are attenuated with leading elliptical holes in vertical and horizontal manner, respectively, in the outer cladding. For the design flexibility, this proposed structure can be gained excellent characteristics like large negative dispersion and high nonlinear coefficient. Due to the great influence on the dispersion properties, only a single material usually silica is used for the proposed PCF. The refractive index of silica has been considered through Sellmier's equation.

3 Synopsis of numerical method

The FEM (Finite Element Method) belongs to a circular perfectly matched layer boundary condition is applied to carry out the numerical simulation for investigating the guiding characteristics of the proposed structure for dispersion compensation. By applying FEM, Maxwell's vectorial equation [25] is solved to best approximate the value of modal effective refractive indexes n_{eff}. Once, the modal effective indices (n_{eff}) are obtained by Eq. (2). Moreover, the dispersion coefficient $D(\lambda)$, nonlinear coefficient (γ) and effective area (A_{eff}), effective V parameter (V_{eff}) can be determined using the Eqs. (3)–(6) formulated in [26, 27]. To investigate the modal characteristics of the proposed PCF, commercial full vector finite-element software (COMSOL 4.2) is used. The background of the proposed square-lattice fiber usually is taken to be silica whose refractive index has been obtained through the following Sellmier's equation:

$$n^2(\lambda) = 1 + \frac{(B_1\lambda^2)}{(\lambda^2 - \lambda_1^2)} + \frac{(B_2\lambda^2)}{(\lambda^2 - \lambda_2^2)} + \frac{(B_3\lambda^2)}{(\lambda^2 - \lambda_3^2)} \tag{1}$$

In addition, some vital issues of designing the PCFs such as dispersion coefficient D, nonlinear coefficient γ, effective area A_{eff} and effective V parameter V_{eff} will be described.

The model effective indices (n_{eff}) are gained as the function of wavelength and material dispersion [$n_{\text{m}}(\lambda)$]. So that

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

where, β is the propagation constant, $k_0=\frac{2\pi}{\lambda}$ is the wave number of free space and $n_m(\lambda)$ can be estimated using the Sellemeier's formula.

The dispersion characteristics can be easily controlled by changing the shape, size and pitch of the air holes. The dispersion coefficient $D(\lambda)$ is calculated from the effective index of the fundamental mode n_{eff} versus the wavelength using the following equation:

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

where, λ is the wavelength, c is the velocity of light in vacuum, $Re\left[n_{eff}\right]$ is the real part of effective indices obtained from simulations.

However, the nonlinear coefficient γ is evaluated as:

$$\gamma = \left(\frac{2\pi}{\lambda}\right)\left(\frac{n_2}{A_{eff}}\right) \tag{4}$$

where, A_{eff} is the effective area which can be determined by the following equation.

$$A_{\text{eff}} = \frac{\left(\int\int |E|^2 dxdy\right)^2}{\int\int |E|^4 dxdy}\ \mu m^2 \tag{5}$$

where, E is the electric field.

Now, it was consciously investigated the mode property of the proposed S-PCF. According to effective V parameter, it is seen that single modes of the fiber is changed inside the telecom band. V_{eff} parameter for the S-PCF can be calculated [28] by applying the following equation,

$$V_{\text{eff}} = \frac{2\pi\wedge}{\lambda}\sqrt{(n_{\text{core}}{}^2 - n_{\text{eff}}{}^2)} \tag{6}$$

Equation (6) is applied to verify the single mode behavior of the proposed design where $\frac{2\pi\Lambda}{\lambda}$ denotes the wave number in the free space and Λ is the pitch; n_{eff} and n_{core} represent the effective index and refractive index of core, respectively.

4 Numerical results and discussion

At the operating wavelength of 1550 nm, the fundamental mode field distribution of the proposed S-PCF is exhibited in Fig. 2 for both x and y polarization modes. For broadband dispersion compensation, it is observed that the dispersion curve influences a negative dispersion slope of standard photonic single mode fiber. The observation results clearly represent that optical field is closely confined to the core region due to high-index contrast in the center than the cladding. The dispersion coefficient is achieved to be −1694.80 ps/(nm-km) at the operating wavelength of 1550 nm, which is higher than [29]. The proposed PCF exhibits tumid design pliability in tailoring dispersion coefficient and nonlinearity in an advanced way in contrast to the standard SMF.

To control dispersion coefficient, there are four degrees of independence in the proposed structure denoted as Λ, d, d_a and d_b. For x-polarization and y-polarization modes, the dispersion coefficient of the proposed S-PCF as a function of wavelength with the considered design parameters of Λ = 0.76 μm, d_b/d_a = 0.67, d_a = 0.72 μm, d_b = 0.48 μm and d = 0.72 μm is shown in Fig. 3. From this figure, it can be seen that the proposed PCF represents a large negative dispersion coefficient about −1694.80 and −1051.60 ps/(nm-km) for x-polarization and y-polarization modes, respectively, at the operating wavelength of 1550 nm. The dispersion values vary from −584.60 to −2337.60 ps/(nm-km) and −540.80 to −1323.30 ps/(nm-km) for X and Y polarization, respectively, around the spectral range of 1340–1640 nm. It is explicit that the x-polarization mode shows higher dispersion compared to that of the y-polarization mode. From above investigation, it is figured out x-polarized mode to acquire optimum results like large negative dispersion, as well as high non-linear coefficient which overcome the limitation of [29] that contains low dispersion coefficient (approximately −555.93 ps/(nm-km)).

Figure 4 demonstrates the effect of air holes on dispersion coefficient in the position of 3rd and 5th layers. In the operating wavelength of 1550 nm, the dispersions are −1694.80 and −862.38 ps/(nm-km) if the air holes in the position of 3rd and 5th layers are elliptical and circular, respectively. From above figure, it is evidently represented that it can be achieved large dispersion coefficient by arranging the air holes at 3rd and 5th layers which

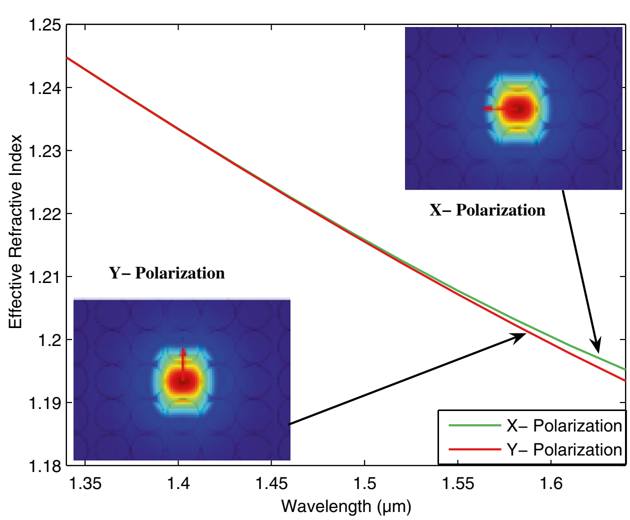

Fig. 2 Field distributions of fundamental modes at wavelength 1550 nm for x-polarization and y-polarization

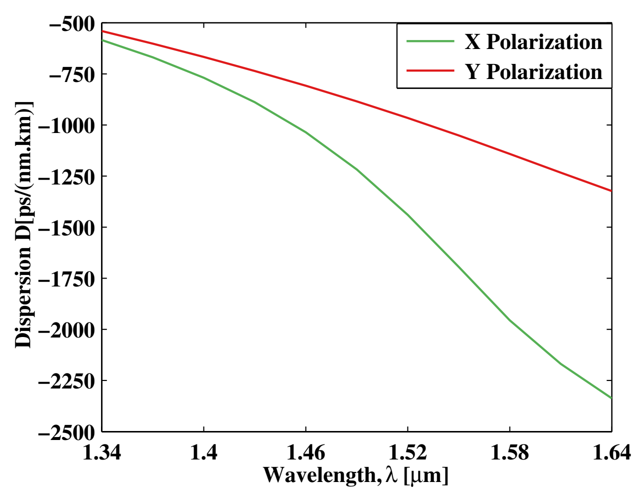

Fig. 3 Dispersion coefficient versus wavelength for the proposed S-PCF for the optimum design parameters: Λ = 0.76 μm, d_b/d_a = 0.67, d = 0.72 μm, d_a = 0.72 μm and d_b = 0.48 μm

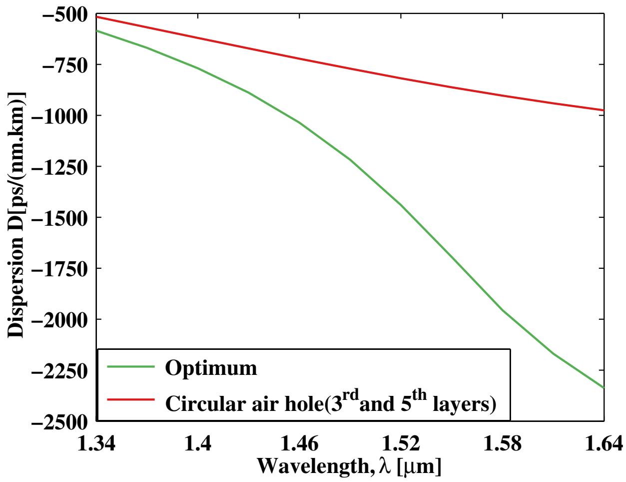

Fig. 4 Dispersion coefficient versus wavelength for the proposed S-PCF for the optimum design parameters: Λ = 0.76 μm, d = 0.72 μm, d_a = 0.72 μm and d_b = 0.48 μm, d_b/d_a = 0.67 and the effect of air holes on dispersion coefficient in the position of 3rd and 5th layers

are compatible for optical communication. The dispersion value of the proposed PCF at 1550 nm is about −1694.80 ps/(nm-km) which exceeds the dispersion values of conventional dispersion compensating fibers (typically −588 ps/(nm-km)) [30].

Figure 5 exhibits the effect of d_a on the dispersion behavior when the other parameters (Λ = 0.76 μm, d_a = 0.72 μm and d_b = 0.48 μm and d_b/d_a = 0.67) are kept constant. Now, the variations of d as 0.71, 0.72 and 0.73 μm, the calculated dispersion coefficients at the wavelength 1550 nm are −1563.10, −1694.80 and −1861.50 ps/(nm-km), respectively. From above investigation, it is clearly reported that dispersion coefficient negatively promotes by increasing the air holes diameter d. Due to this, the optical field is strongly absorbed into the core region which leads to achieve highly negative dispersion, as well as very high nonlinear coefficient than [31].

From Fig. 6, it can be seen that dispersion coefficient negatively increases by decreasing the elliptical air holes diameter (d_a) at 3rd and 5th layers in the direction of the major axis. According to the variation of d_a as 0.71, 0.72 and 0.73 μm, the calculated dispersion coefficients at 1550 nm are −1761.00, −1694.80 and −1635.50 ps/(nm-km), respectively, by keeping other parameters (Λ = 0.76 μm, d = 0.72 μm and d_b = 0.48 μm) to constant. By the comparison of Figs. 5 and 6, it can be seen that the diameter of circular air holes at 1st, 2nd and 4th layers should be increased and alleviated the elliptical air holes at 3rd and 5th layers, as much as possible to achieve highly negative dispersion for the purpose of broadband communication [32].

Figure 7 represents the variation of elliptical air holes diameter (d_b) at 3rd and 5th layers in the direction of the minor axis that have a great effect on dispersion coefficient when the other parameters (Λ = 0.76 μm, d = 0.72 μm and d_a = 0.72 μm) are kept fixed. From this figure, it can be noticed that by reducing the air holes diameter (d_b) large negative dispersion coefficient as well as high non-linearity can be achieved. It can be also regarded that the effect of d_b is more significant on dispersion than d_a to acquire the expected dispersion coefficient. According to this figure, the variation of d_b as 0.47, 0.48 and 0.49 μm considered the dispersion coefficients at 1550 nm are −1892.60, −1694.80 and −1543.40 ps/(nm-km), respectively.

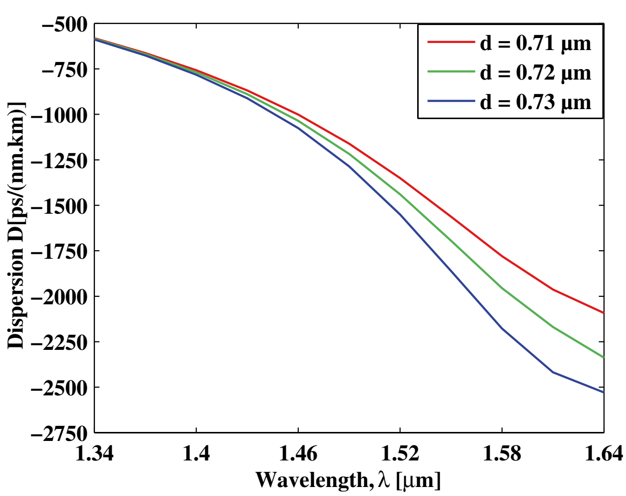

Fig. 5 Dispersion coefficient versus wavelength for the proposed S-PCF for the optimum design parameters: Λ = 0.76 μm, d_b/d_a = 0.67, d_a = 0.72 μm, d_b = 0.48 μm, d = 0.71, 72 and 73 μm

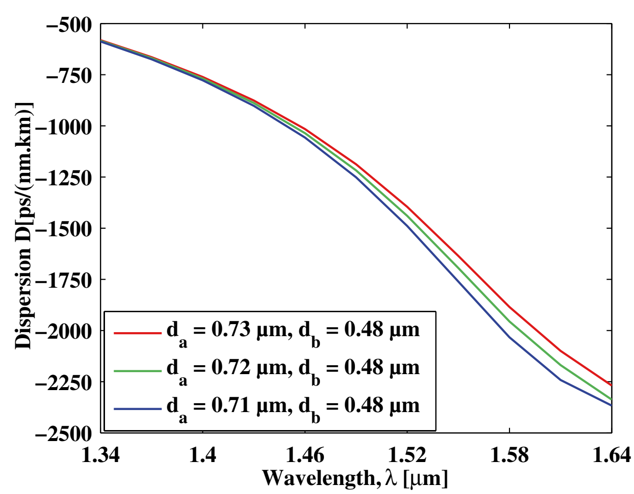

Fig. 6 Dispersion versus wavelength for the proposed S-PCF for the optimum design parameters: Λ = 0.76 μm, d = 0.72 μm, d_b/d_a = 0.67, d_a = 0.71, 0.72 and 0.73 μm, d_b = 0.48 μm

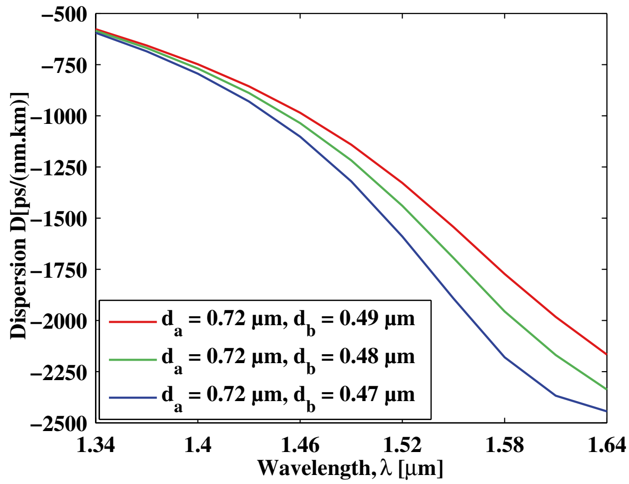

Fig. 7 Dispersion versus wavelength for the proposed S-PCF for the optimum design parameters: $\Lambda = 0.76$ μm, $d = 0.72$ μm, $d_a = 0.72$ μm, $d_b = 0.47$, 0.48 and 0.49 μm

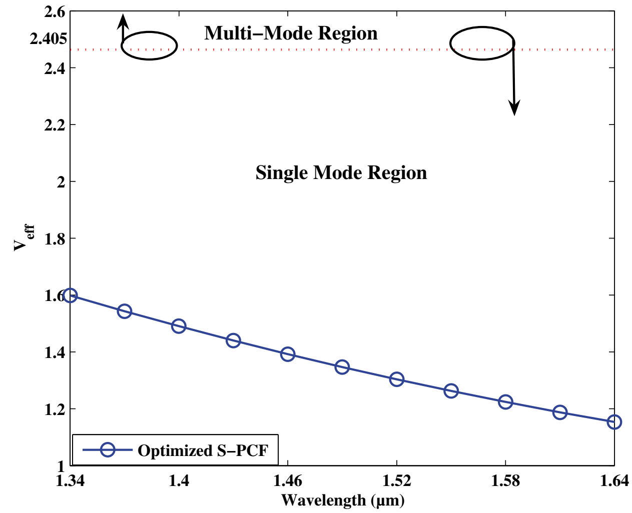

Fig. 9 *V* parameter of the proposed S-PCF as a function of wavelength for $\Lambda = 0.76$ μm, $d_b/d_a = 0.67$, $d_a = 0.72$ μm, $d_b = 0.48$ μm and $d = 0.72$ μm

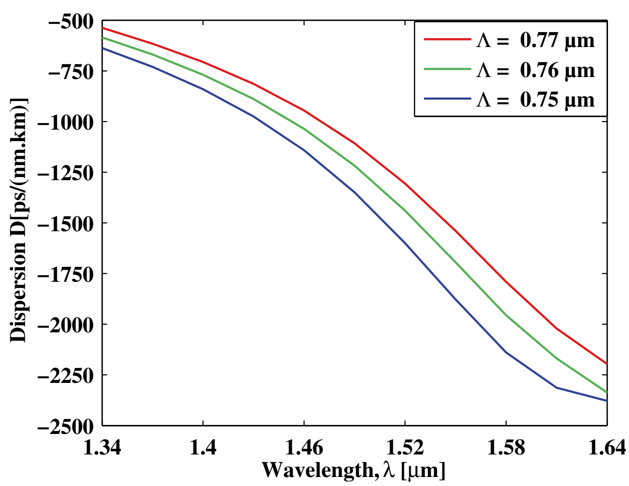

Fig. 8 Dispersion coefficient versus wavelength for the proposed S-PCF for the optimum design parameters: $d_b/d_a = 0.67$, $d = 0.72$ μm, $d_a = 0.72$ μm, $d_b = 0.48$ μm, $\Lambda = 0.75$, 0.76 and $\Lambda = 0.77$ μm

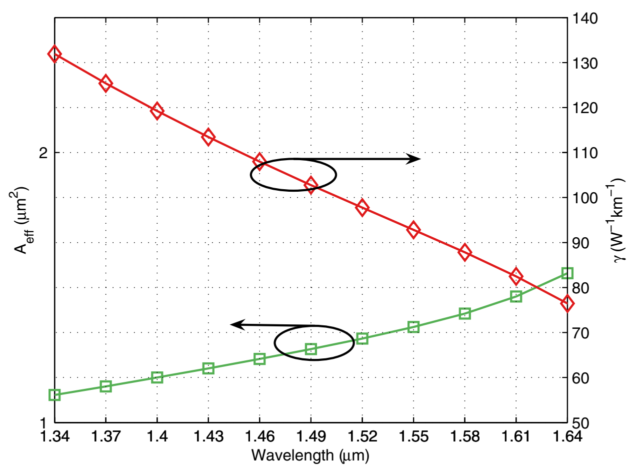

Fig. 10 Effective area and nonlinear coefficient for x-polarization mode of the proposed S-PCF as a function of wavelength for $\Lambda = 0.76$ μm, $d_b/d_a = 0.67$, $d_a = 0.72$ μm, $d_b = 0.48$ μm and $d = 0.72$ μm

Figure 8 shows the effect of pitch variation on dispersion coefficient when the other parameters $d_a = 0.72$ μm, $d_b = 0.48$ μm and $d = 0.72$ μm are kept constant. Now, the pitch (Λ) variations are considered as 0.75, 0.76 and 0.77 μm, as well as the calculated dispersion coefficients at 1550 nm are −1877.80, −1694.80 and −1539.30 ps/(nm-km), respectively. It is definitely represented that the large negative dispersion coefficient can be achieved by reducing pitch for broadband dispersion compensation. For broadband communication, it is also regarded that the PCF can compensate the dispersion coefficient about 2.93 times than [34].

The single-mode operation of the proposed S-PCF can be evaluated using *V* effective (V_{eff}) parameter. Figure 9 demonstrates the V_{eff} parameter as a function of wavelength with optimized design parameters of $\Lambda = 0.76$ μm, $d = 0.72$ μm, $d_a = 0.72$ μm and $d_b = 0.48$ μm. The V_{eff} parameter can be achieved by the expression (6). With approximate perfect electric and magnetic conductor boundary condition, it has been used FEM at the outer enclosure to obtain the index of space-filling mode [28]. At operating wavelength 1550 nm, the V_{eff} parameter for a single mode fiber (SMF) is $V_{eff} \leq 2.405$ [32]. From Fig. 9, it can be seen that the achieved V_{eff} value is about 1.26 at wavelength 1550 nm which is less than 2.405 in the whole band of interest. According to simulation, it is clearly investigated that the proposed S-PCF acts as an SMF over the whole bands.

Figure 10 illustrates the effective area and nonlinear coefficient of the proposed S-PCF as a function of wavelength for the optimized parameters, $\Lambda = 0.76$ μm, $d_a = 0.72$ μm, $d_b = 0.48$ μm and $d = 0.72$ μm. The figure also represents that effective area enhances according to the wavelength. The mode power closely demarked in the core region at the longer wavelength, so the guiding waves diverse largely. Due to this, the propagating modes retain larger effective area. An opposite behavior can be seen for the nonlinear coefficient, which is also demonstrated in Fig. 10. The effective area at 1550 nm has been achieved to be about 1.35 μm^2 and the coinciding nonlinear coefficient is about 92.83 W^{-1} km^{-1} which is higher than [34]. The inflictions of such higher nonlinear coefficient can be seen in the super continuum generation and optical code-division-multiple-access [35].

The dispersion coefficient is achieved to be −1694.80 ps/(nm-km) at the operating wavelength of 1550 nm which is definitely higher than [29]. After plotting the dispersion curve to the expected level (Fig. 3), then it has been investigated, the dispersion validity of the proposed design S-PCF. During the fabrication process, ±1% variations of global parameters may occur in a standard fiber draw [30]. To ensure dispersion tolerance, there may require an accuracy of ±2%. In our proposed PCF, global parameters are varied up to 2% to gain better dispersion accuracy. Figure 11 demonstrates the corresponding dispersion curve with variations of global parameters ±1% and ±2%. At the wavelength 1550 nm, the dispersion coefficient can be achieved −1844.80, −2006.60 ps/(nm-km) and −1546.60, −1409.80 ps/(nm-km) by decreasing and increasing the global parameters order of 1 and 2%, respectively. In such situation, it is proven that the dispersion curve provides a negative dispersion which is a precondition for wide-band dispersion compensation of usual single mode fiber.

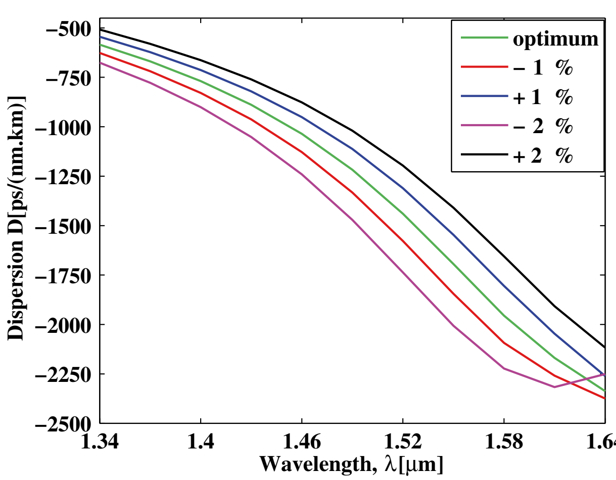

Fig. 11 Dispersion properties of S-PCF: optimum design parameters and fiber's global parameters variations of order ±1 and ±2% around the optimum value

Finally, a comparison is applied between characteristics of the S-PCF and some other conventional design for dispersion compensation applications. Table 1 represents the discrimination taking into account dispersion (D), the nonlinear coefficient (γ) and effective area (A_{eff}). From Table 1, it is clearly visualized that our proposed PCF exhibits superior result not only in case of dispersion but also in the case of nonlinear coefficient. Our proposed PCF gains about 2.14, 1.61, 3.05 and 2.93 times higher negative dispersion compared with [29–32, 34] respectively. In addition, the nonlinear coefficient is about 2.38 and 1.75 times higher than [30, 34] respectively. So, it definitely demonstrates that the proposed PCF is better for dispersion compensation, as well as highly nonlinear coefficient than prior PCFs. Our proposed PCF also exhibits simplicity in design compared to prior PCFs [29, 30]. So the fundamental task likes fabrication process comparatively easy.

Finally, it will be investigated the fabrication flexibility of the proposed structure. In Fig. 1, it can be represented that it forms of square lattice in the cladding that gives additional efficiency during fabrication. The conventional stack and draw technique is perfect for fabrication of the PCF because this method gives a good degree of exactness for closed-packed geometry like triangular or honeycomb lattice [31]. On the other hand, the drilling method offers adjustment of both holes size and spacing, as well as can procreate circular shapes perfectly. In such situations, PCFs that consist of elliptical holes were experimentally fabricated in 2004 [36]. However, by current advanced technology, the proposed structure can be fabricated for technological advancement in the fabrication of PCFs. The sol–gel technique provided by Bise et al. [33] is used to fabricate the PCFs with all structures and they also offer the freedom to adjust air-hole size, shape, and spacing. In addition, the sol–gel casting method offers design flexibility that will be perfect for the proposed PCF.

Table 1 Comparison between properties of the proposed S-PCF and prior PCFs at 1550 nm wavelength

Ref.	D [ps/(nm-km)]	$\gamma(W^{-1}\ km^{-1})$	$A_{eff}\ (\mu m^2)$
[29]	−555.93	–	2.63
[30]	−588.00	–	3.43
[31]	−790.12	–	1.64
[32]	−1054.40	39.00	–
[34]	−578.50	53.10	2.44
Proposed PCF	−1694.80	92.83	1.35

5 Conclusion

In this article, a single-mode large negative dispersion, as well as high non-linear coefficient wide-band dispersion compensating S-PCF has been offered based on square-lattice geometry PCF. The numerical investigations reveal that the proposed design offers highly negative dispersion and very high non-linear coefficient ranging from about −584.60 to −2337.60 ps/(nm-km) and 131.91 to 61.40 W^{-1} km^{-1}, respectively, over 1340–1640 nm wavelength bands. The investigations definitely exhibit that at the time of drawing the fiber, the dispersion conduct does not vary much even if there are several variations of the design parameters. Due to the luscious index-guiding characteristics, the proposed design will be compatible for broadband dispersion compensation in polarization-maintaining and high-speed transmission system applications. It is also expected that the proposed S-PCF will be effective for numerous future applications like wide-band dispersion compensation in PM devices, high-bit-rate transmission networks, and sensing systems.

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References

1. Rabiul Hasan, M., Hasan, M.I., Shamim Anower, M.: Tellurite glass defect-core spiral photonic crystal fiber with low loss and large negative flattened dispersion over S + C + L + U wavelength bands. Appl. Optics. **54**(32), 9456 (2015)
2. Knight, J.C.: Photonic crystal fibres. Nature **424**(6950), 847–851 (2003)
3. Zsigri, B., Lægsgaard, J., Bjarklev, A.: A novel photonic crystal fibre design for dispersion compensation. J. Opt. A Pure Appl. Opt. **6**(7), 717–720 (2004)
4. Litchinitser, N.M., Eggleton, B.J., Patterson, D.B.: Fiber Bragg gratings for dispersion compensation in transmission: theoretical model and design criteria for nearly ideal pulse recompression. J. Lightwave Technol. **15**(8), 1303–1313 (1997)
5. Bulow, H., Buchali, F., Klekamp, A.: Electronic dispersion compensation. J. Lightwave Technol. **26**(1) 158–167 (2008)
6. Watanabe, S., Naito, T., Chikama, T.: Compensation of chromatic dispersion in a single-mode fiber by optical phase conjugation. IEEE Photon. Technol. Lett. **5**(1) 92–95 (1993)
7. Broeng, J., Mogilevstev, D., Barkou, S.E., Bjarklev, A.: Photonic crystal fibers: A new class of optical Waveguides. Opt. Fiber Technol. **5**(3), 305–330 (1999)
8. Shen, L.P., Huang, W., Chen, G.X., Jian, S.S.: Design and optimization of photonic crystal fibers for broad-band dispersion compensation. IEEE Photon. Technol. Lett. **15**(4), 540–542 (2003)
9. Huttunen, A., Torma, P.: "Optimization of dual-core and microstructure fiber geometries for dispersion compensation and large mode area". Opt. Express. **13**(2), 627 (2005)
10. Prabhakar, G., Peer, A., Rastogi, V., Kumar, A.: Large-effective-area dispersion-compensating fiber design based on dual-core microstructure. Appl. Opt. **52**(19), 4505 (2013)
11. Maji, P.S., Chaudhuri, P.R.: Design of ultra large negative dispersion PCF with selectively tunable liquid infiltration for dispersion compensation. Opt. Commun. **325**, 134–143 (2014)
12. X. Zhao et al.: Photonic crystal fiber for dispersion compensation. Appl. Opt. **47**(28), 5190 (2008)
13. Maji, P.S., Chaudhuri, P.R.: Designing an ultra-negative dispersion Photonic crystal fiber with square-lattice geometry. ISRN Opt. **2014**, 1–7 (2014)
14. Poli, F. et al.: Single-mode regime of square-lattice photonic crystal fibers. J. Opt. Soc. Am. A, **22**(8), 1655 (2005)
15. Bouk, A.H., Cucinotta, A., Poli, F., Selleri, S.: Dispersion properties of square-lattice photonic crystal fibers. Opt. Express. **12**(5), 941 (2004)
16. Birks, T.A., Mogilevtsev, D., Knight, J.C., St. Russell, P.J.: Dispersion compensation using single-material fibers. IEEE Photon. Technol. Lett. **11**(6), 674–676, (1999)
17. Yang, S., et al.: "Theoretical study and experimental fabrication of high negative dispersion photonic crystal fiber with large area mode field". Opt. Express. **14**(7), 3015 (2006)
18. Matsui, T., Nakajima, K., Sankawa, I.: Dispersion compensation over all the telecommunication bands with double-cladding Photonic-Crystal fiber. J. Lightwave Technol. **25**(3), 757–762, (2007)
19. Yokokawa, T., Kato, T., Fujii, T., Yamamoto, Y., Honma, N., Kataoka, A., Onishi, M., Sasaoka, E., Okamoto, K.: Dispersion compensating fiber with large negative dispersion around 300 ps/km/nm and its application to compact module for dispersion adjustment. Opt. Fiber Commun. CON. **2**, 717–719(2003)
20. Roberts, P.J. et al.: Control of dispersion in photonic crystal fibers. J. Opt. Fiber Commun. Rep. **2**(5), 435–461, (2005)
21. Yang, S., Zhang, Y., He, L., Xie, S.: Broadband dispersion-compensating photonic crystal fiber. Opt. Lett. **31**(19), 2830, (2006)
22. Poli, F., Cucinotta, A., Selleri, S., Bouk, A.H.: Tailoring of flattened dispersion in highly Nonlinear Photonic crystal fibers. IEEE Photon. Technol. Lett. **16**(4), 1065–1067, (2004)
23. Lee, M.K., Ma, P.S., Lee, I.K., Kim, H.W., Kim, Y.Y.: Negative refraction experiments with guided shear-horizontal waves in thin phononic crystal plates. Appl. Phys. Lett. **98**(1), 011909, (2011)
24. Maji, P.S., Roy Chaudhuri, P.: Dispersion properties of the square-lattice elliptical-core PCFs. Am. J. Opt. Photonics (AJOP). **2**(1), 1–6, (2014)
25. Saitoh, K., Koshiba, M.: Full-vectorial imaginary-distance beam propagation method based on a finite element scheme: application to photonic crystal fibers. IEEE J. Quantum Electron. **38**(7), 927–933, (2002)
26. Selim Habib, M., Samiul Habib, M., Abdur Razzak, S.M., Namihira, Y., Hossain, M.A., Goffar Khan, M.A.: Broadband dispersion compensation of conventional single mode fibers using microstructure optical fibers. Optik-Int. J. Light Electron Opt. **124**(19), 3851–3855, (2013)
27. Kaijage, S.F., et al.: Broadband dispersion compensating octagonal Photonic crystal fiber for optical communication applications. Jpn. J. Appl. Phys. **48**(5), 052401, (2009)
28. Mortensen, N.A., Folkenberg, J.R., Nielsen, M.D., Hansen, K.P.: Modal cutoff and the V parameter in photonic crystal fibers. Opt. Lett. **28**(20), 1879, (2003)
29. Hasan, M.I., Selim Habib, M., Samiul Habib, M., Abdur Razzak, S.M.: Highly nonlinear and highly birefringent dispersion compensating photonic crystal fiber. Opt. Fiber Technol. **20**(1), 32–38, (2014)
30. Selim Habib, M., Samiul Habib, M., Abdur Razzak, S.M., Anwar Hossain, M.: Proposal for highly birefringent broadband

dispersion compensating octagonal photonic crystal fiber. Opt. Fiber Technol. **19**(5), 461–467, (2013)
31. Haque, M.M., Rahman, M.S., Habib, M.S., Razzak, S.M.A.: Design and characterization of single mode circular photonic crystal fiber for broadband dispersion compensation. Optik-Int. J. Light Electron Opt. **125**(11), 2608–2611, (2014)
32. Hasan, M.I., Habib, M.S., Razzak, S.M.A.: Design of hybrid photonic crystal fiber: Polarization and dispersion properties. Photon. Nanostructures Fundam. Appl. **12**(2), 205–211, (2014)
33. Hamzaoui, H.El, et al.: Sol-gel derived ionic copper-doped microstructured optical fiber: a potential selective ultraviolet radiation dosimeter. Opt. Express. **20**(28), 29751, (2012)
34. Hasan, M.R., Islam, M.A., Rifat, A.A.: A single-mode highly birefringent dispersion-compensating photonic crystal fiber using hybrid cladding. J. Mod. Opt. **64**(3), 218–225, (2017)
35. Lee, J.H.et al.: A holey fiber-based nonlinear thresholding device for optical CDMA receiver performance enhancement. IEEE Photon. Technol. Lett. **14**(6), 876–878, (2002)
36. Issa, N.A., van Eijkelenborg, M.A., Henry, G., Fellew, M., Large, M.C.: Fabrication and characterization of microstructured optical fibres with elliptical holes. In *Conference on Lasers and Electro-Optics* (p. CThX3). Optical Society of America, Washington, DC, (2004)