Front. Optoelectron. 2020, 13(4): 433–440
https://doi.org/10.1007/s12200-019-0948-8

RESEARCH ARTICLE

Highly nonlinear bored core hexagonal photonic crystal fiber (BC-HPCF) with ultra-high negative dispersion for fiber optic transmission system

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Abstract In this paper, we propose a bored core hexagonal photonic crystal fiber (BC-HPCF) which obtains ultra-high negative dispersion and large nonlinearity simultaneously. The aim of the proposed design is to achieve the desired optical properties by using circular air holes only to make the fiber simple and manufacturable. To investigate the light guiding properties of the proposed BC-HPCF, finite element method (FEM) with circular perfectly matched boundary layer (PML) is used. According to numerical simulation, it is possible to obtain a large value of negative dispersion of $-2102\ \mathrm{ps\cdot nm^{-1}\cdot km^{-1}}$ and large value of nonlinearity of $111.6\ \mathrm{W^{-1}\cdot km^{-1}}$ at optimum wavelength of 1550 nm. In addition, $\pm 2\%$ deviation in optical characteristics is evaluated and reported in order to study the practical feasibility of the proposed BC-HPCF. The large negative dispersion and high nonlinearity of our proposed design make it a strong candidate for optical broadband communication, super continuum generation, and sensing.

Keywords photonic crystal fiber (PCF), dispersion, nonlinearity, optical broadband communication

1 Introduction

Photonic crystal fibers (PCFs) are a new kind of microstructure optical fibers that exhibit high optical functions with the help of the wave guiding properties. The cross section of a systematic PCF structure is composed of lattice air holes on a background, usually silica. The cross-sectional arrangement of lattice air holes determines the dissemination of the refractive index. By establishing defects at the center of the PCF structure where the light guiding takes place as a result of total internal reflection similar to conventional fibers solid core can be formed. By adjusting the spatial parameter designs such as position and size of the lattice holes preferred optical characteristics in PCF can be acquired [1,2]. Large negative dispersion [3], high nonlinearity [4], high birefringence [5], and design flexibility provided by PCFs make these structures a favorable technology replacement to ordinary optical fibers in telecommunication [6], laser [7], and various sensor-based application [8].

The splitting of light wave into its distinct spectral components because of the difference in wavelength-dependent velocity is a phenomenon known as chromatic dispersion. This phenomenon is the reason of expansion of light pulse in optical fibers which leads to the fall of signal quality. Dispersion compensating fibers (DCFs) which display a large negative dispersion are used in long haul optical communication to make the net effective dispersion zero [9,10]. Another optical property which qualifies PCF to draw remarkable attention with great research interest is optical nonlinearity. The effective mode area and nonlinear refractive index of the silica are fundamentally responsible for the nonlinear coefficient of PCF. Particular applications such as wavelength conversion, optical parametric amplification, and supercontinuum generation require PCFs with enriched nonlinear optical properties.

Several PCF designs have been investigated on dispersion and nonlinearity by adjusting the PCF structural parameters. In 2013, Wang et al. designed a new kind of hybrid structure photonic crystal fiber for achieving high birefringence and large negative dispersion. However, the inner core of the reported hybrid structure contains rectangular shaped air holes and reported dispersion was around $-300\ \mathrm{ps\cdot nm^{-1}\cdot km^{-1}}$ [11]. In 2015, Haque et al. developed a new type of circular PCF using hybrid cladding structure to investigate the optical guiding

Received June 24, 2019; accepted August 16, 2019

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characteristics and revealed high nonlinearity of 45.5 $W^{-1}\cdot km^{-1}$ and dispersion of -650 $ps\cdot nm^{-1}\cdot km^{-1}$. The main limitation of the reported PCF includes design complexity, larger effective area and smaller negative dispersion [12]. Islam et al. proposed an ultrahigh negative dispersion compensating regular five rings square PCF using non-circular air holes in the outer three rings and circular air holes in the inner two rings which achieves a large value of dispersion of -1694.80 $ps\cdot nm^{-1}\cdot km^{-1}$ and nonlinearity of 92.83 $W^{-1}\cdot km^{-1}$ [13]. However, fabrication complexity is the major pitfall of this design. To overcome fabrication difficulties, in 2019, Islam et al. designed a new class of single mode all circular square photonic crystal fiber and reported ultra-high negative dispersion of -2015.30 $ps\cdot nm^{-1}\cdot km^{-1}$ and nonlinearity of 99.73 $W^{-1}\cdot km^{-1}$ [14]. In 2019, Saha et al. reported a highly nonlinear PCF using both circular and non-circular air holes in the core-cladding region. The reported PCF revealed a high negative dispersion of -540.67 $ps\cdot nm^{-1}\cdot km^{-1}$, birefringence of 2.75×10^{-2}, and nonlinearity of 43.7 $W^{-1}\cdot km^{-1}$ [15]. However, the reported value is much smaller as well as fabrication process becomes challenging due to use of non-circular air holes.

Recently, we designed a modified hexagonal photonic crystal fiber to analyze dispersion and birefringence characteristics and reported an ultra-high birefringence of 4.321×10^{-2} and dispersion of -1044 $ps\cdot nm^{-1}\cdot km^{-1}$ [16]. In this study, we propose a highly nonlinear bored core hexagonal photonic crystal fiber (BC-HPCF) by taking into account the fabrication complexity. The proposed BC-HPCF consists only circular shape air holes to make the fabrication process much easier. In addition, asymmetry in the core region is introduced by inserting eight smaller circular air holes with equal radius to obtain ultra-high negative dispersion as well as large nonlinearity. Refractive index profile of the core is changed significantly due to asymmetry in the core region which in turn produced an ultra-high negative dispersion of -2102 $ps\cdot nm^{-1}\cdot km^{-1}$ at 1550 nm wavelength. Furthermore, the proposed BC-HPCF has a large nonlinearity of 111.6 $W^{-1}\cdot km^{-1}$ at 1550 nm.

2 Design structure of the proposed BC-HPCF

Figure 1 delineates the geometrical plan of the proposed BC-HPCF structure on xy plane with circular arrangement of air holes (i.e., dark circles) on a solitary foundation material, silica (i.e., white region of internal circle). Geometric structure of the designed PCF consists of five rings of circular air holes with three different types of diameter. The separation between the focuses of two adjacent air openings is called pitch Λ. The core of the crystal is bored, i.e., filled with circular air holes, in a specific pattern to achieve high dispersion and nonlinearity. To analyze the various wave guiding properties of the proposed BC-HPCF structure, single layer circular perfectly matched layer (PML) is used uniformly around the proposed BC-HPCF structure with a thickness of 1 μm and a scaling factor of 1. Finer mesh is applied to the entire structure. In addition, to investigate the dispersion and nonlinear properties of the BC-HPCF, size and position of air holes is adjusted accordingly. Moreover, to achieve effectively large nonlinearity eight circular air holes with d_0 diameter is included inside the core. As the core region is contained a large number of air holes than conventional HPCF, optical field is strongly confined inside the core region. Changing the position and diameter of air holes leads to a change in effective refractive index which effectively increase negative dispersion.

Size: The air holes in the first ring are sharing equal diameters of d_1. The air holes have a place in the last four rings have an equivalent diameter of d_2. Eight extra air holes placed in the core are sharing equal diameter d_0.

Position: Three different distance is used inside the core to enhance the dispersion property of the designed BC-HPCF (r_1 represents the distance between center to air holes No. 4 and No. 8 where the x-axis distance is x_1 and y-axis distance is zero, r_2 represents the distance between center to air holes No. 2 and No. 6 where the x-axis distance is zero and y-axis distance is y_1, r_3 represents the distance between center to air holes No. 1, No. 3, No. 5 and No. 7 where the x-axis distance is x_2 and y-axis distance is y_2). The design has been picked especially to upgrade the negative dispersion and nonlinear properties of the proposed BC-HPCF by taking into account fabrication issue. Eight smaller air holes inside the core significantly reduces the refractive index and effective area. In addition, position of air holes inside the core has been shifted to increase the asymmetry inside the center area. The proposed fiber has four degrees of freedom, i.e., d_0, d_1, d_2 and Λ. Changing these geometrical parameters will initiate change in the optical modular properties, for example, dispersion, nonlinearity, and birefringence of the proposed PCF.

3 Numerical method

Numerical simulation has been carried out to explore the optical managing properties of the proposed BC-HPCF structure utilizing full vector finite element method-based software COMSOL Multiphysics. To absorb unwanted radiation and enhance light confinement inside the core, a circular PML with thickness 1 μm is used. Effective refractive index n_{eff} of the fundamental mode is directly proportional to mode propagation constant β, and inversely proportional to wave number k_0, and is written as

$$n_{\mathrm{eff}} = \frac{\beta(\lambda, n_{\mathrm{m}}(\lambda))}{k_0}.$$

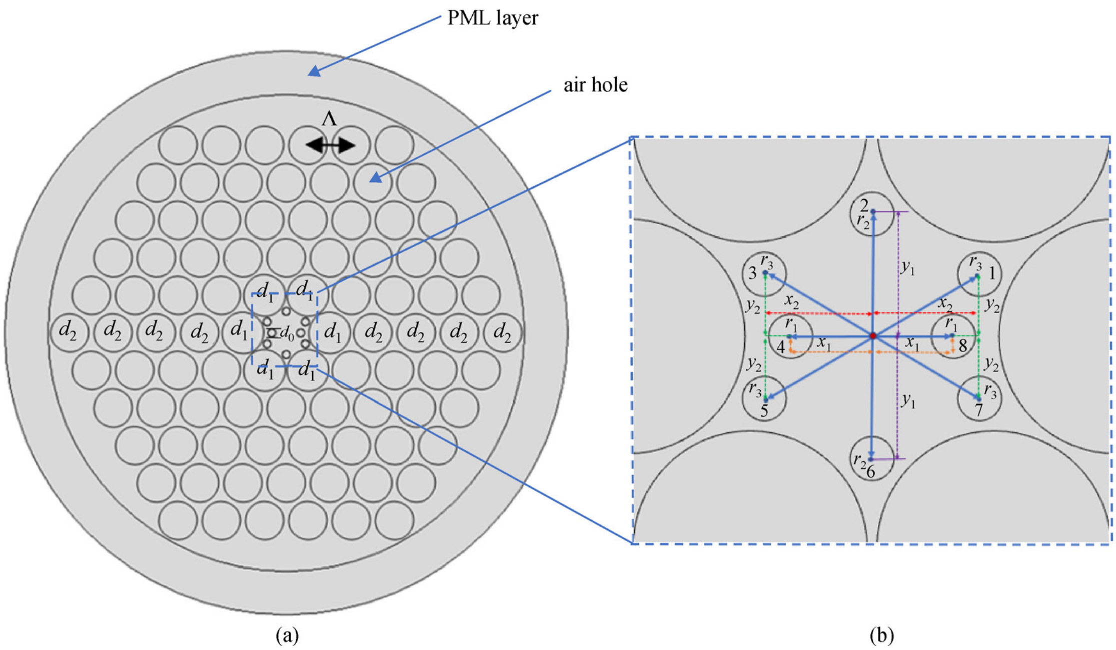

Fig. 1 Cross-sectional view of the proposed BC-HPCF. (a) Transverse section of the proposed PCF; (b) geometry of the core of the proposed PCF

Here, $n_{\mathrm{m}}(\lambda)$ is material dispersion and can be estimated by using the Sellemeier's formula.

Fused silica is used as a background material of the proposed BC-HPCF whose refractive index can be evaluated by utilizing Sellmeier's equation as pursues:

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

where, $C_1 = 4.67914826 \times 10^{-3}$ μm^2, $C_2 = 1.35120631 \times 10^{-2}$ μm^2, $C_3 = 97.9340025$ μm^2, $B_1 = 0.6961663$, $B_2 = 0.4079426$ and $B_3 = 0.8974794$ are Sellmeier coefficients of the material. The values of the Sellmeier coefficients rely upon both material and temperature.

Dispersion properties of the designed BC-HPCF can be tuned by adjusting the air hole size, shape and position. Chromatic dispersion is strongly depending on real part of effective refractive index and can be calculated using following equation

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

where the unit of dispersion is ps·nm^{-1}·km^{-1}, and the speed of light in vacuum is c.

However, effective mode area A_{eff} is evaluated as

$$A_{\mathrm{eff}} = \frac{\left(\iint |E|^2\mathrm{d}x\mathrm{d}y\right)^2}{\iint |E|^4\mathrm{d}x\mathrm{d}y},$$

where E is the electric field, and the effective area of the fundamental mode is expressed in μm^2. Effective mode area is inversely related to nonlinearity and used to measure the impact of nonlinear coefficient on the proposed fiber geometry. The nonlinearity γ of the PCFs depends firmly on the Kerr constant n_2 of the material and can be calculated using following equation

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

where the unit of the nonlinearity is W^{-1}·km^{-1}.

4 Simulation result and discussion

In this section, the guiding properties of the proposed fiber are investigated by adjusting the geometrical structural parameters such as pitch, and diameter. Figures 2(a) and 2(b) delineate the strong confinement of light inside the fiber core of the designed BC-HPCF for both x and y polarization at 1550 nm wavelength. In Fig. 2(c), the simulation result exhibits large dispersion of -2059 and -2102 ps·nm^{-1}·km^{-1} for both x and y polarization at 1550 nm, respectively using optimum design parameters. In addition, we also investigate the convergence of the proposed design to evaluate the accuracy of the solution.

Figure 3 delineates the impact of dispersion properties of the proposed BC-HPCF on pitch variation, where the other geometric parameters are kept constant. We have varied the

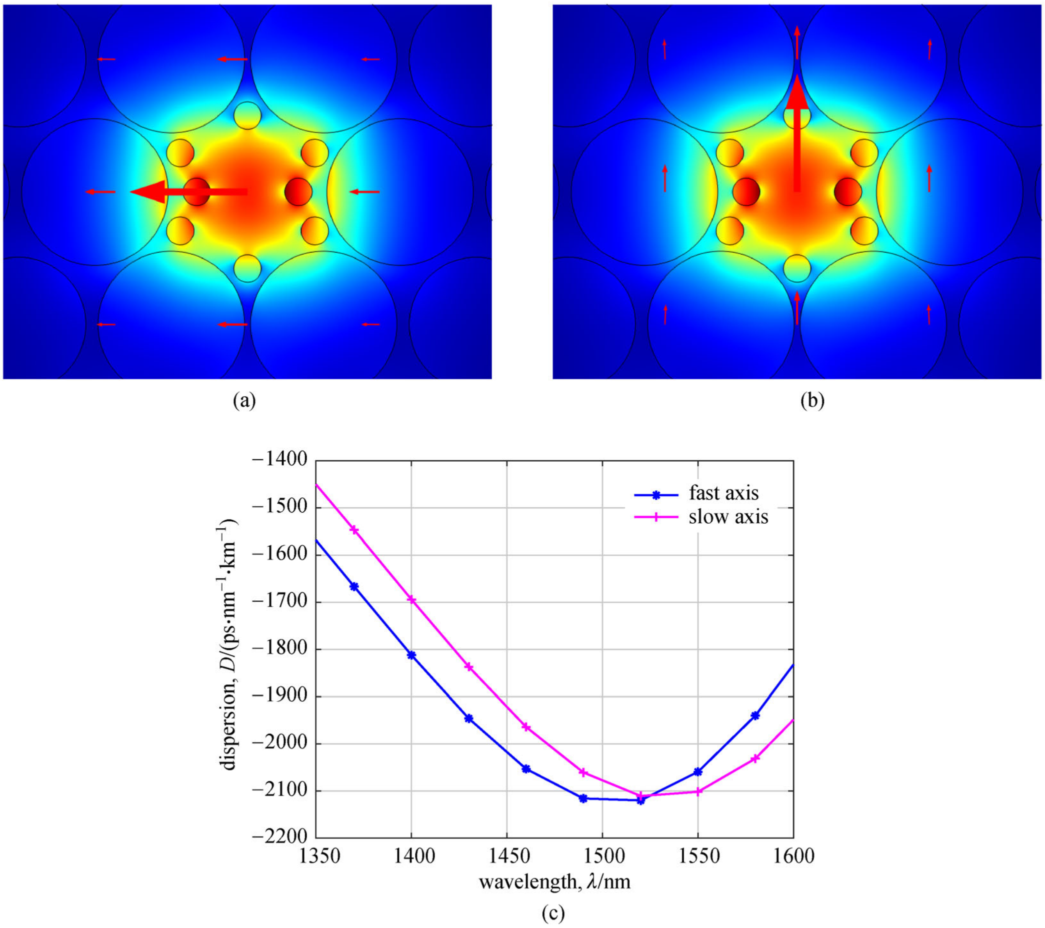

Fig. 2 (a) Electric field distribution at communication wavelength for x polarization; (b) electric field distribution at communication wavelength for y polarization; (c) wavelength-dependent dispersion coefficient of the proposed BC-HPCF for both polarizations for optimum geometrical parameters: $\Lambda = 0.82$ µm, $d_1/\Lambda = 0.96$, $d_2/\Lambda = 0.88$, and $d_0/\Lambda = 0.18$

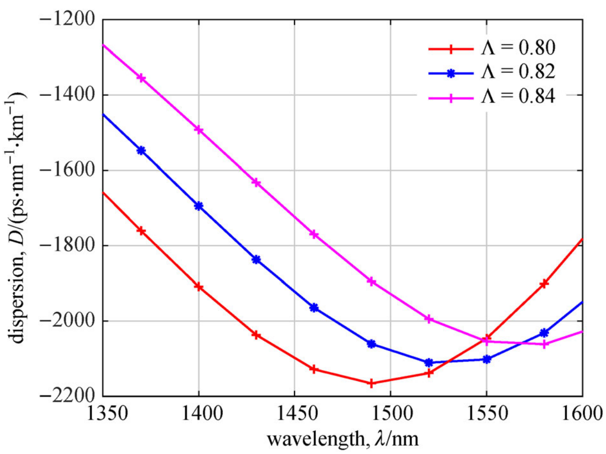

Fig. 3 Wavelength dependent dispersion coefficient for the variation of Λ

adjacent distance between air holes from 0.80 to 0.84 to investigate the dispersion properties. Numerical simulation results confirm that the proposed BC-HPCF achieved larger negative dispersion for smaller value of pitch at excitation wavelength of 1550 nm. The refractive index profile of the proposed BC-HPCF change significantly as distance between air holes decreases. The calculated dispersion for the pitch value of 0.80, 0.82, 0.84 are −2046, −2102, and −2054 ps·nm^{-1}·km^{-1}, respectively at 1550 nm.

Figures 4(a) and 4(b) show the impact of diameter, d_1/Λ variation on dispersion and nonlinearity while other geometric parameters are remain fixed. The investigation results also demonstrate that dispersion slope can be effectively controlled by changing d_1/Λ. From Fig. 4(a), it can be seen that dispersion slope increases as d_1/Λ changes from 0.94 to 0.98. The calculated dispersions for the diameter $d_1/\Lambda = 0.94$, 0.96, 0.98 are −1776, −2102, and −2415 ps·nm^{-1}·km^{-1} respectively, at 1550 nm. To enhance strong confinement of light inside the core, diameter d_1/Λ is set to 0.96 which is much larger value as compared with other diameters of the proposed BC-HPCF. Figure 4(b) delineates the linear increase of nonlinearity as

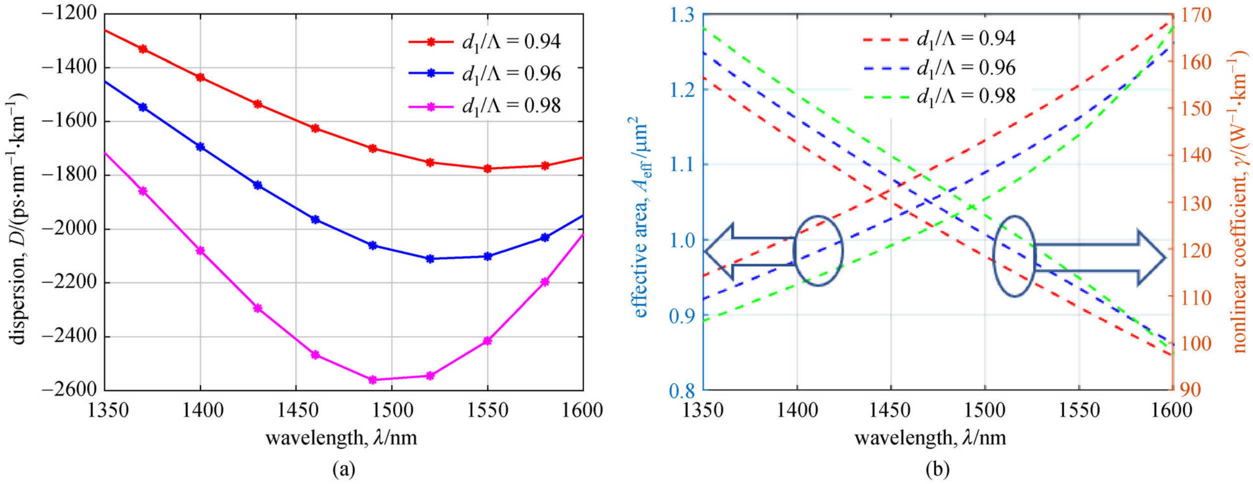

Fig. 4 (**a**) Wavelength dependent dispersion coefficient for the variation of d_1/Λ; (b) effective mode area and nonlinear coefficient of the designed BC-HPCF as a function of wavelength for the variation of d_1/Λ

a function wavelength. Enhanced nonlinearity can be achieved for the proposed structure due to use of large diameter $d_1/\Lambda = 0.96$. This leads to smaller effective mode area. The nonlinearities of the proposed structure for the diameter $d_1/\Lambda = 0.94$, 0.96, 0.98 are 107.6, 111.6 and 113.9 $\mathrm{W^{-1}\cdot km^{-1}}$, respectively at 1550 nm wavelength. The optimum value of nonlinearities is 111.6 $\mathrm{W^{-1}\cdot km^{-1}}$ which is comparatively much larger than that reported in Ref. [15].

To analyze the impact of dispersion and nonlinear properties of the proposed BC-HPCF due to diameter d_2/Λ variation, a parametric investigation has been carried out using finite element method-based software Comsol Multiphysics. Figure 5(a) shows the dispersion characteristics due to change in the diameter d_2/Λ while $d_1/\Lambda = 0.96$, $d_0/\Lambda = 0.18$ and $\Lambda = 0.82$, are kept fixed. When diameter d_2/Λ is changed to 0.86, 0.88, and 0.90, the measured dispersions are −2166, −2102, and −1829 $\mathrm{ps\cdot nm^{-1}\cdot km^{-1}}$, respectively at optimum wavelength 1550 nm. As d_2/Λ decreases from 0.90 to 0.86 with constant d_1/Λ, d_0/Λ and pitch, the refractive index changes significantly outside the core which leads to change in refractive index profile inside the core. Therefore, a significant dispersion of −2166 $\mathrm{ps\cdot nm^{-1}\cdot km^{-1}}$ can be found when $d_2/\Lambda = 0.86$ at 1550 nm wavelength. The effective area and optical nonlinearity of the proposed BC-HPCF for the variation of d_2/Λ are illustrated in Fig. 5(b). From Fig. 5(b), it can be clearly seen that smaller effective area is observed at lower wavelength and nonlinearity decreases almost linearly as a function of wavelength. An optimum nonlinearity of 111.6 $\mathrm{W^{-1}\cdot km^{-1}}$ is achieved at excitation wavelength of 1550 nm when $d_2/\Lambda = 0.88$. The calculated nonlinearities for the designed BC-HPCF are 106.9 and 110.5 $\mathrm{W^{-1}\cdot km^{-1}}$ when d_2/Λ is changed to 0.86, and 0.90, respectively at 1550 nm.

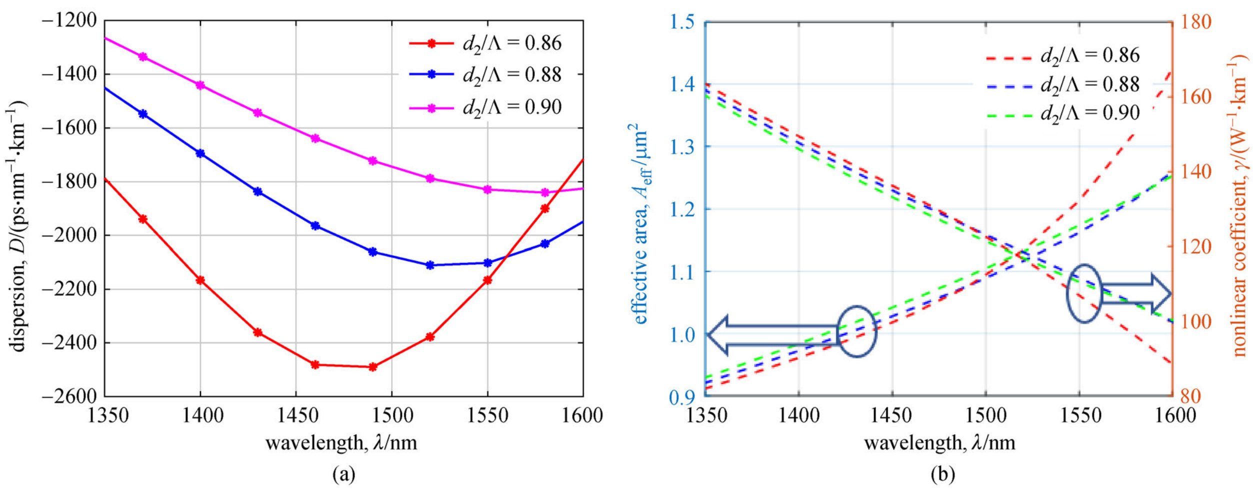

Fig. 5 (a) Wavelength dependent dispersion coefficient for the variation of d_2/Λ; (b) effective mode area and nonlinear coefficient of the designed BC-HPCF as a function of wavelength for the variation of d_2/Λ

The novelty of the proposed BC-HPCF arises due to use of eight smaller air holes of diameter $d_0/\Lambda = 0.18$ inside the first ring. These eight air holes significantly alter the refractive index profile of the proposed BC-HPCF which leads to enhance optical properties such as dispersion and nonlinearity. Chromatic dispersion of the simulated BC-HPCF structure as a function of wavelength for the variation of d_0/Λ is plotted in Fig. 6(a). At communication wavelength, the proposed BC-HPCF shows ultra-high negative dispersion of -2102 ps·nm^{-1}·km^{-1} when $d_0/\Lambda = 0.18$, $d_1/\Lambda = 0.96$, $d_2/\Lambda = 0.88$ and pitch $\Lambda = 0.82$ μm. However, the estimated value of negative dispersion at communication wavelength are -2035, -2102, -1981 ps·nm^{-1}·km^{-1} for $d_0/\Lambda = 0.16$, 0.18, and 0.20, respectively. BC-HPCF structure with eight air holes inside the core shows a smaller effective mode area at communication wavelength. As a result, significant amount of light is confined inside the core. However, the effective mode area increases with an increase in the wavelength. As stated earlier, the effective mode area is inversely proportional to the nonlinear coefficient. The relation between obtained effective mode area and nonlinearity due to variation of d_0/Λ at different operating wavelength is plotted in Fig. 6(b). At communication wavelength, BC-HPCF structure reports an effective nonlinearity of 111.6 W^{-1}·km^{-1}.

Furthermore, considering the manufacturing issue, more studies have been carried out to investigate the impact of the pitch fluctuation on the proposed BC-HPCF's optical properties. ±2% fabrication tolerance due to variation of geometrical parameters can be considered during fabrication process. Figures 7(a) and 7(b) reveal the wavelength dependence dispersion characteristics and nonlinearity of the projected BC-HPCF structure for ±2% variation in pitch. From Fig. 7(a), it is noted that the change in pitch

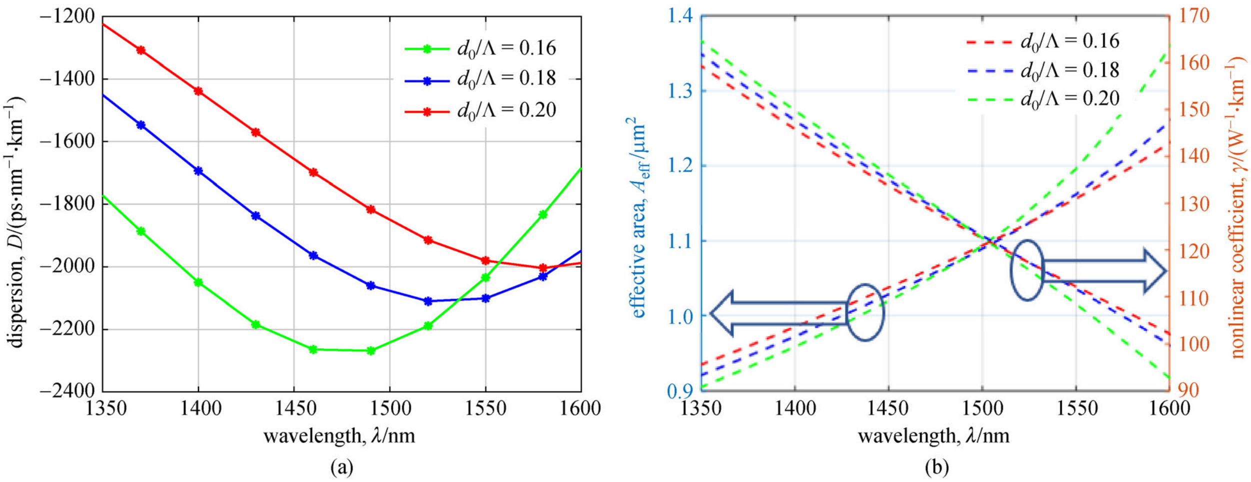

Fig. 6 (a) Wavelength dependent dispersion coefficient for the variation of d_0/Λ; (b) effective mode area and nonlinear coefficient of the designed BC-HPCF as a function of wavelength for the variation of d_0/Λ

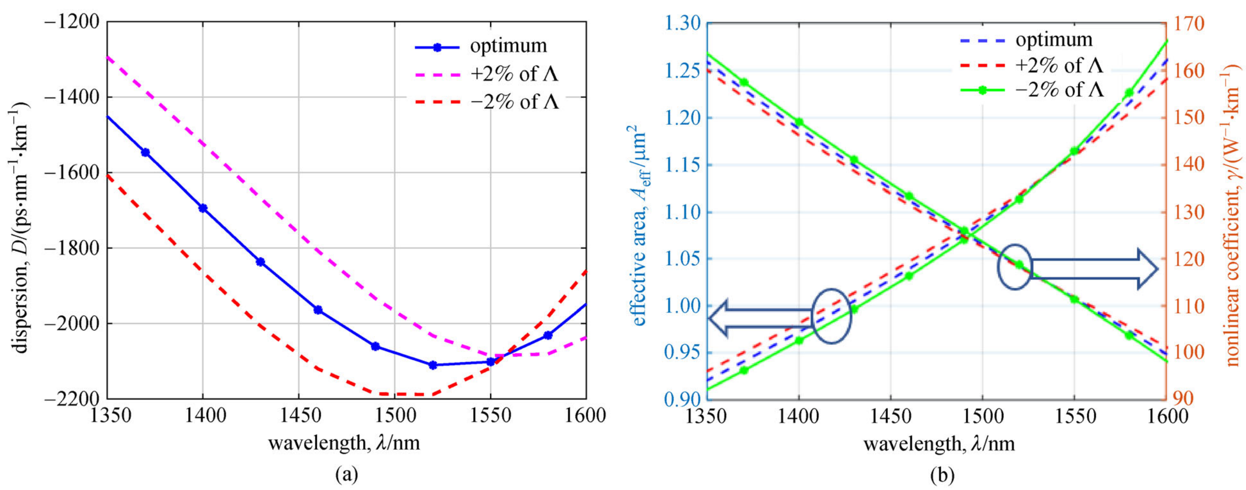

Fig. 7 (a) Wavelength dependent dispersion coefficient for the variation of ±2% pitch; (b) effective mode area and nonlinear coefficient of the designed BC-HPCF as a function of wavelength for the variation of ±2% pitch

Table 1 Comparison table on the contemporary PCF structures with the proposed BC-HPCF at 1550 nm wavelength

prior reference	air hole shape	dispersion, $D(\lambda)$ /(ps·nm^{-1}·km^{-1})	nonlinearity, γ /(W^{-1}·km^{-1})	air hole structure
[13]	circular and elliptical	−1694.80	92.83	square
[14]	circular and elliptical	−2015.30	99.73	square
[15]	circular and elliptical	−540.67	43.70	hybrid
[16]	circular	−1044	77.85	hexagonal
[17]	circular and elliptical	−1528	84.80	square
[18]	circular	−753.2	96.51	hexagonal
proposed BC-HPCF		−2102	111.6	hexagonal

does not have any significant change in dispersion properties and it also shows almost same value at communication wavelength for negative or positive swing of pitch value. However, nonlinearity of the projected BC-HPCF ranges from 111.4 to 111.9 W^{-1}·km^{-1} at communication wavelength due to ±2% variation in pitch. Therefore, the projected fiber can be fabricated accurately using current fabrication technology due to negligible effect of pitch variation on dispersion and nonlinear properties.

Finally, Table 1 compares the proposed fiber with some other recent works by taking into account the dispersion and nonlinear properties. From Table 1, it can be clearly concluded that the proposed BC-HPCF demonstrate ultra-high negative dispersion with large nonlinearity. The square PCF design proposed in Refs. [13] and [14] comprise of both circular and noncircular air holes which allow the structure to procure substantial dispersion and strong nonlinearity. In addition, the existence of non-circular airholes in the PCF makes the fabrication process demanding. All the circular air holes encompassed in the PCF design recommended in Refs. [16] and [18] exhibit dispersion values that are 2.01 and 2.79 times lower than our recommended design. All other PCF designs mentioned in the above optical properties are surpassed by our recommended design which provides adjustability in the fabrication process.

One of the major objectives of our proposed design is to satisfy the adjustability of the fabrication process. A large number of fabrication techniques (i.e., conventional drilling, stack and draw method, and sol-gel casting) are used to fabricate the microstructure fiber of asymmetric and complex structure. Conventional drilling method is widely used to adjust the size and spacing of air holes. However, this method is limited to circular shape geometry [19]. The stack and draw method provides manageability over the shape of the core and index profile of the cladding region in a sustainable way [20]. Sol-gel techniques have provided added advantage over conventional drilling method that it can be able to fabricate any shape of structure including elliptical or rectangular shape [21]. Our proposed BC-HPCF consists only circular air holes and diameter of the smaller air hole is 114.76 nm. To numerically investigate the optical light guiding property, similar type of diameter has also been reported. Recently, Wiederhecker et al. [22] fabricated smaller air hole of 110 nm diameter using stack and draw technique. Our design has the diameter of 114.76 nm which is higher than the fabrication dimension reported in Ref. [22]. Thus, we believe that the proposed structure can be executed with acceptable accuracy of the optimal design parameters.

5 Conclusions

In conclusion, in this paper, a highly nonlinear dispersion compensating five rings index guiding photonic crystal fiber with bored core is proposed in the wavelength range from 1350 to 1700 nm. To investigate the numerical analysis, FEM techniques are used. Circular perfectly matched boundary layer is used instead of square PML to minimize the confinement loss. Numerical results reveal that it can be possible to obtain high nonlinearity of 111.6 W^{-1}·km^{-1} and dispersion of −2102 ps·nm^{-1}·km^{-1} at 1550 nm by adjusting the structural parameters of the proposed BC-HPCF. In addition, the proposed BC-HPCF can be easily fabricated using current fabrication method. In terms of nonlinearity and negative dispersion, the proposed BC-HPCF has much larger value than those reported in Refs. [13,17]. Therefore, the proposed BC-HPCF can be suitable for the application in high data rate optical communication system and a range of nonlinear applications such as supercontinuum generation, and sensing.

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