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Ultra-high Birefringent Photonic Crystal Fiber for Sensing Applications

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ABSTRACT

We proposed a novel structure of photonic crystal fiber (PCF) which provides ultra-high birefringence with ultra low confinement loss for sensing application. Finite element method is used to characterize the modal properties of our proposed PCF. According to Simulation we found ultra high birefringence of 2.962×10^{-2} at operating wavelength 1550nm. The proposed PCF also offers large value of negative dispersion coefficient of – 354.3 ps/(nm.km), large value of nonlinear coefficient of 66.36 $W^{-1}km^{-1}$, and ultra low confinement loss in the order of 10^{-5}.

Keywords: Photonic crystal fiber; Nonlinear coefficient; Ultra-high birefringence

1. Introduction

In the recent years photonic crystal fibers (PCFs) have attracted significant consideration of researchers because of their remarkable characteristics including high birefringence, large nonlinearity and large negative value of dispersion due to flexible design parameter compared to ordinary optical fiber. A large number of the research paper has published recently on photonic crystal fiber for the application of sensing and high bit rate communication system [1-11]. Among the features of PCFs, birefringence is one of the most interesting characteristics. High birefringence can be easily obtained due to large index difference and design flexibility in photonic crystal fibers. So far, a number of designs of highly birefringent PCFs have been reported. For achieving ultra high birefringence different types of air holes arrangement in the core as well as cladding is proposed. Wang et. al have proposed a high birefringence of 1.83×10^{-2}, photonic crystal fiber (PCF) using the complex unit cells in cladding [9].

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To achieve ultra high birefringence and large negative dispersion several efforts have been taken by different research groups. An Octagonal MOF structure have been proposed in [10] which exhibits high birefringence of 1.67×10-2 and large value of negative dispersion of 239.5 ps/(nm.km). Another group have proposed a new PCF structure that offers high value of negative dispersion of - 300 ps/(nm.km). Matsui et al. have designed a new structure that covers E, S, L bands but it require large fiber for dispersion compensation because of low dispersion [12]. Furthermore, ultra high birefringence photonic crystal fibers with large nonlinearity have been widely used for the application of sensing and super-continuum (SC) generation [13].

In this paper, we designed a simple hexagonal photonic crystal fiber for simplifying the fabrication process. The main advantage of our proposed structure is the design flexibility along with ultra high birefringence and large nonlinearity for sensing applications. Our proposed photonic crystal fiber also offers large value of negative dispersion which is widely used for broadband communication network. Most importantly our proposed PCF minimize the fabrication complexity by using circular air holes in the cladding region and elliptical air holes in 1st ring of PCF. According to simulations, the designed PCF exhibits ultra high birefringence of 2.962×10^{-2} and large negative dispersion of -354.3ps/(nm.km) at the excitation wavelength of 1550 nm.

2. DESIGN METHODOLOGY

Fig. 1 exhibits the transverse cross section of our designed PCF which contains five air hole layers. Second, third, fourth and fifth layers consist of circular air holes and first layer consist of elliptical and semicircular air holes. The reason behind using semicircular and elliptical air holes is to gain ultrahigh birefringence and large nonlinearity. The proposed PCF consists of five rings in which the air holes diameters of three rings are equal which denoted by d. We used silica as a

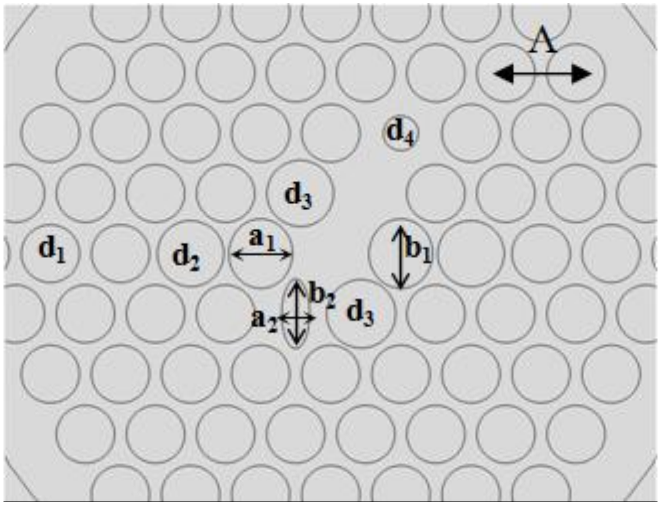


Fig. 1 Transverse cross section of proposed H-PCF where, $\Lambda=0.91\mu m$, $d_1/\Lambda=0.83$, $d_2/\Lambda=0.95$, $d_3/\Lambda=0.9$, $d_4/\Lambda=0.5$ and for elliptical air holes $a_1/\Lambda=0.83$ & $b_1/\Lambda=0.91$, $a_2/\Lambda=0.36$ & $b_2/\Lambda=0.91$.

main material in our designed hexagonal photonic crystal fiber. To attain high birefringence asymmetry is introduced inside the core and makes it semicircular shape. The major and minor axis of two elliptical air holes are defined as $a_1/\Lambda = 0.83$ & $b_1/\Lambda = 0.91$, $a_2/\Lambda = 0.36$ & $b_2/\Lambda = 0.91$ and the other two semicircular air holes diameter is about $d_3/\Lambda = 0.9$. Depending on pitch value we found that our proposed PCF shows negative dispersion characteristics. At the core region, the one air-hole with d1 diameter is disabled to further improve the birefringence. The refractive index of fiber silica is 1.45 and refractive index of air-hole is 1.

3. Numerical results and discussions

The Finite element method (FEM) is used to investigate the properties of our proposed hexagonal photonic crystal fiber. Circular perfectly matched layers (PML) boundary condition is applied to carry out the numerical simulation. Commercial full-vector finite-element software (COMSOL) 4.2 is used to calculate the confinement loss, dispersion and birefringence. The background material of our proposed hexagonal PCF is silica whose refractive index has been obtained by using well known Sellmeier equation. Chromatic dispersion $D(\lambda)$, confinement loss L_c and birefringence B can be calculated by the following equations [14].

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

$$L_c = 8.686 \times \mathrm{k}_0 \mathrm{Im}[\mathrm{n}_{\mathrm{eff}}] \times 10^3 \, dB/km$$

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

where, $\operatorname{Re}[n_{eff}]$ is the real part of refractive index n_{eff} and $\mathrm{Im}[\mathrm{n}_{\mathrm{eff}}]$ imaginary part of effective refractive index n_{eff}, λ denote the wavelength, c denote the light velocity and k_0 denotes the wave number in free space.

The effective mode area A_{eff} is defined as follows [15]:

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

where, A_{eff} is the effective mode area in μm^2 and E is slowly varying electric field amplitude. Effective area is important for studying nonlinear case in optical fiber, microcavity [16-20] as well as photonic crystal fiber. To understand the nonlinear phenomena in photonic crystal fiber, effective mode area is defined. Nonlinearity is directly inversely proportional to the effective mode area i.e for better nonlinearity light must confined in a small area. Nonlinearity in a photonic crystal fiber is defined as follows

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

4. Simulation Results and Discussion

Fig. 2 shows the dispersion characteristics of our designed PCF. In our design, we select pitch, $\Lambda = 0.91\mu m$, $d_1/\Lambda = 0.83$, $d_2/\Lambda = 0.95$, $d_3/\Lambda = 0.9$, $d_4/\Lambda = 0.5$ and for elliptical air holes $a_1/\Lambda = 0.83$ & $b_1/\Lambda = 0.91$, $a_2/\Lambda = 0.36$ & $b_2/\Lambda = 0.91$. Fig. 2 also reveals the pitch variation in accordance with wavelength. We varied the pitch value Λ, ± 1% to ± 2%, and other parameters related to our design kept fixed. In PCF during fabrication ± 1% pitch variation may be occurred [21]. By considering fabrication difficulty, we have briefly explained the impact of dispersion and birefringence properties by changing pitch value ± 1% to ± 2%. The optimum value of negative dispersion of – 354.3 ps/(nm.km) is obtained at excitation wavelength 1550nm which is well enough for the application of dispersion compensating fiber.

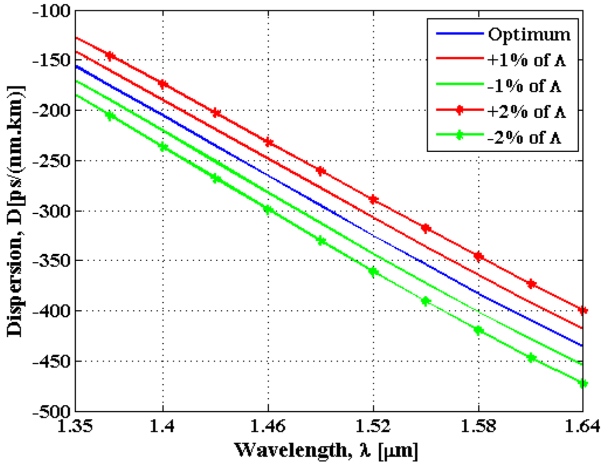


Fig. 2 (a) Wavelength dependence dispersion curve for y polarization

Birefringence characteristics of the proposed ultra high PCF are also shown in fig. 3. Due to the asymmetry in the central core region we found high birefringence of about 2.962×10^{-2} at excitation wavelength 1550 nm. Our results shows ultra high birefringent as compared with other PCFs which is shown in table 1. We varied the pitch from its optimum value by ± 1% to ± 2%, and found that birefringence becomes 0.02885, 0.02934, 0.03001 and 0.03039 respectively at 1550 nm.

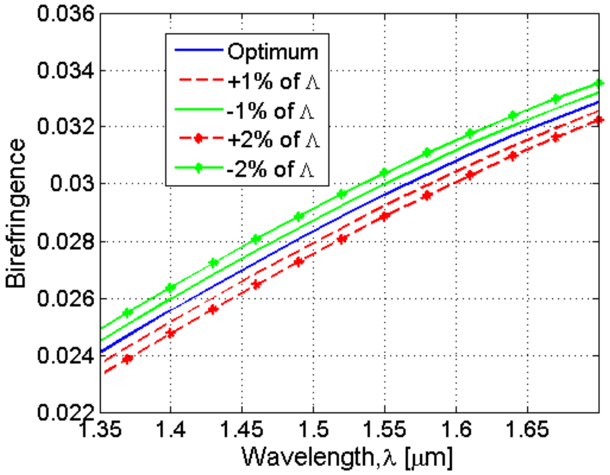
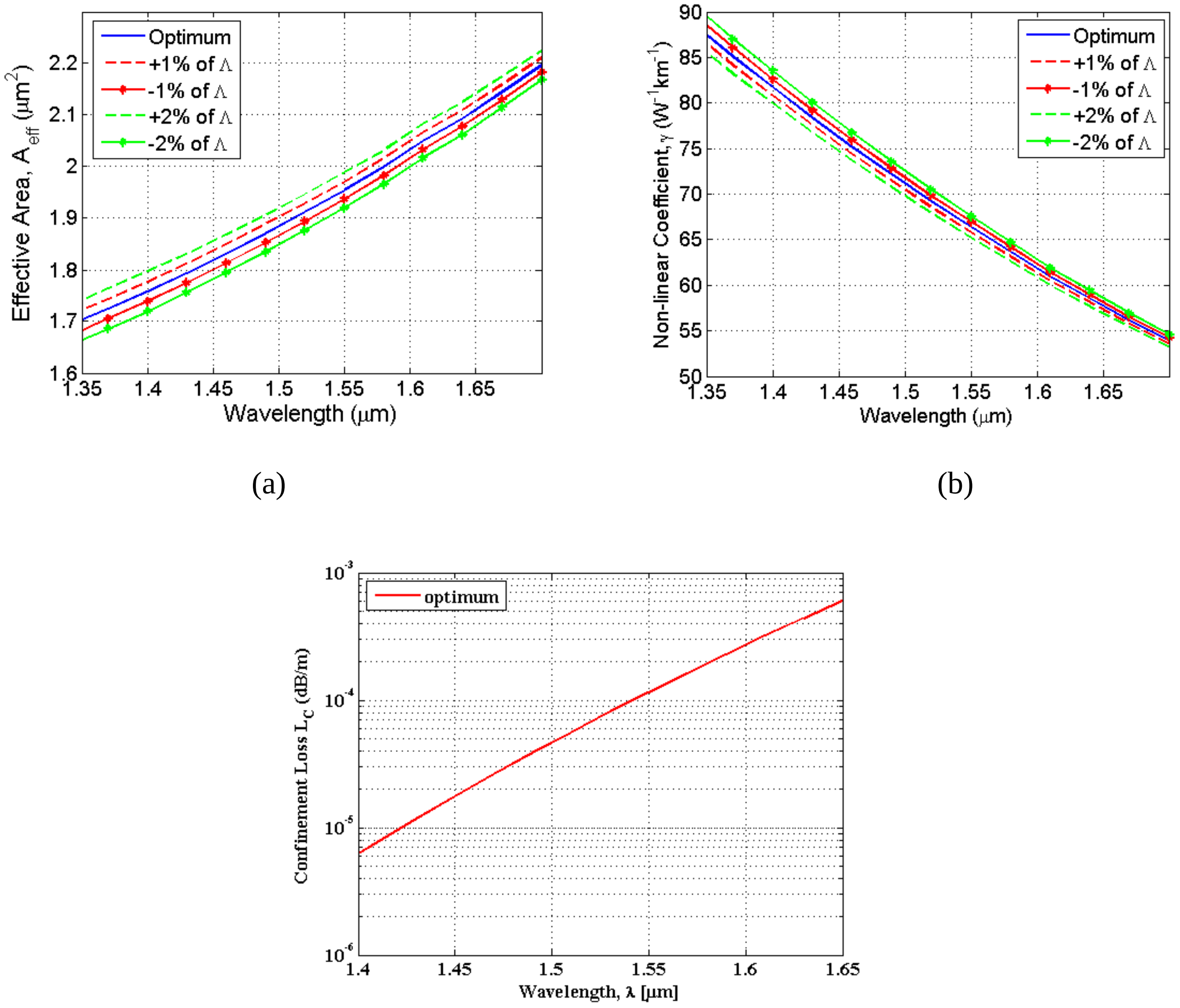


Fig. 3 Birefringence as function of wavelength.

From Fig. 4(a) it can be seen that our proposed PCF exhibits small effective mode area which is well enough for obtaining large nonlinearity. From figure we found effective mode area of our proposed H-PCF is 1.955μm^2 at 1550 nm. Fig. 4(b) shows the nonlinearity versus wavelength for optimum design parameter as well as pitch variation from ± 1% to ± 2%. The value of nonlinear coefficient is 66.36 W^{-1}km^{-1} at 1550 nm wavelength. The value of large nonlinear coefficient is remarkably well enough for the application of sensing and super-continuum generation [22].

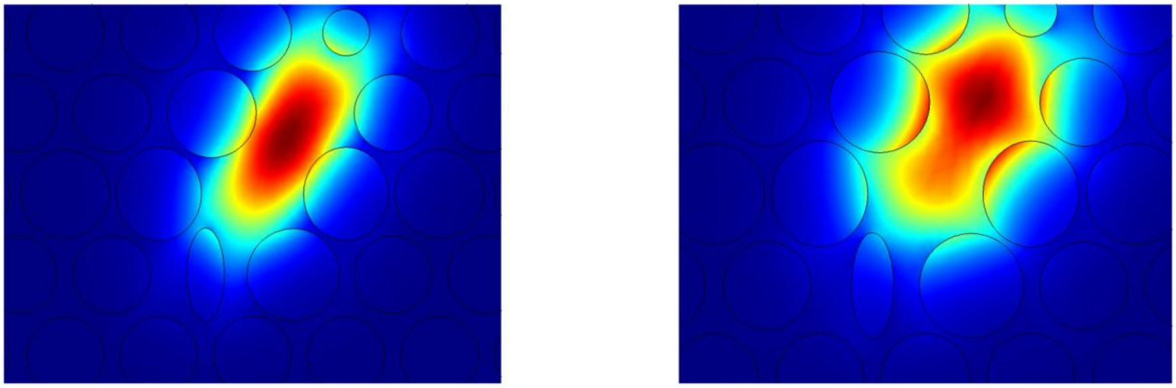


(a) (b)

(c)

Fig. 4 (a) Wavelength dependence effective area **(b)** nonlinear coefficient **(c)** confinement loss curve of proposed H-PCF for optimum design parameters

The optimum value of confinement loss of our proposed ultra high birefringence PCF is shown on the Fig. 4 (c). From figure, we found confinement loss in the order of 10^{-5} at 1550 nm wavelength. It can be observed that our proposed PCF shows ultra low confinement loss as compared with ordinary fiber. So, light strongly confined in the central core region.



(a) (b)

Fig. 5 Optical Field distributions at 1550 nm for (a) x-polarization and (b) y-polarization

Fig. 5 shows the optical field profile for x and y polarization modes at 1550 nm. According to numerical simulation, it can be seen that both x and y polarized modes are strongly confined in the center core region due to high-index contrast in the core region than the cladding region.

Comparison between modal properties of our proposed PCF and other PCFs at 1550 nm is shown in Table I.

Table I Comparison of modal characteristics of our designed PCF and other PCFs

PCFs	**Comparison of modal properties**		
	D(λ) Ps/(nm.km)	**$B=\|n_x–n_y\|$**	**A_{eff} (μm^2)**
Ref. [9]	-------	1.83×10^{-2}	------
Ref. [11]	-300	------	1.55
Ref. [13]	-588	1.81×10^{-2}	3.41
Ref. [21]	-474.5	------	1.60
Ref. [23]	----------	1.75×10^{-2}	3.248
Ref. [24]	-----------	2.62×10^{-2}	-------
Proposed H-PCF	-354.3	2.962×10^{-2}	1.955

5. Conclusions

In summary, a hexagonal microstructure photonic crystal fiber (PCF) has been proposed that simultaneously ensures ultrahigh birefringence and large value of negative dispersion coefficient. We found ultra high birefringence of 2.962×10^{-2} at 1550 nm wavelength. Another important characteristics of our H-PCF fiber is that it offers negative dispersion coefficient of about -354.3 ps/(nm.km) and high nonlinearity of about 66.36 $W^{-1}km^{-1}$ simultaneously. Our proposed PCF can be used for sensing and super continuum generation due to its extraordinary guiding properties.

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