Proposal for an Ultra-high Birefringent Photonic Crystal Fiber with Large Nonlinearity

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ABSTRACT

In this paper a hexagonal microstructure photonic crystal fiber (PCF) is proposed which provides ultra-high birefringence property with ultra low confinement loss for sensing application. Finite element method is used to characterize the guiding properties. 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}. Due to its excellent guiding properties, this design has the excellent capability for sensing applications and broadband dispersion compensation in high-bit rate transmission network.

Keyword : - *Photonic crystal fiber, Nonlinear coefficient, Ultra-high birefringence*

1. INTRODUCTION

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].

To achieve ultra high birefringence and large negative dispersion several attempts have been taken by different 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) but birefringence is not considered here. Matsui et al. have designed a new structure that covers all three communication band but due to its low dispersion value it require large fiber for dispersion compensation [12]. Furthermore, ultra high birefringence photonic crystal fiber with large nonlinearity have received recent rising attention in sensing and super-continuum (SC) applications. The well-preserved polarization state along with the fiber is an anticipated feature for SC generation, as less power is required due to enhanced nonlinear interaction [13].

In this paper, we propose hexagonal photonic crystal fiber having circular air-holes in the fiber cladding which simplifies 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 very decisive for high-bit-rate communication network. Another improvement of proposed PCF is, in our design to diminish the complexity of fabrication process we have used 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 air holes distribution of the proposed photonic crystal fiber which contains five air hole layers. Second, third, fourth and fifth layers consists 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 key material in our proposed structure and air holes are arranged in hexagonal shape. To attain high birefringence four air holes along the y axis in first ring make in 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 rest of the two semicircular air holes diameter is about $d_3/\Lambda = 0.9$. The negative dispersion characteristics is achieved because of the value of pitch Λ=0.91μm. 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.

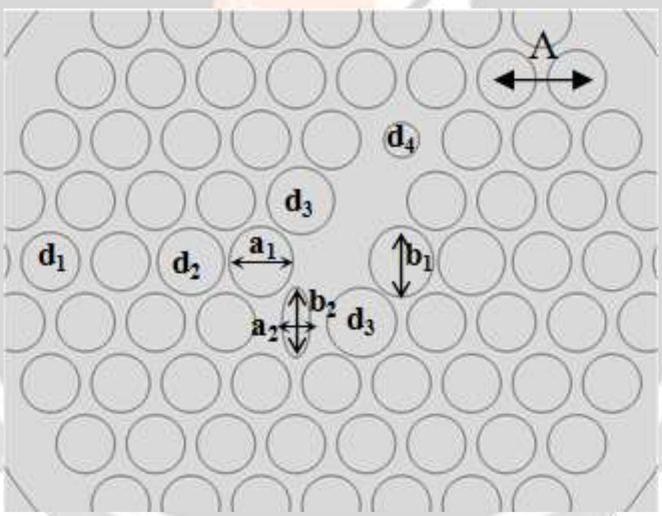


Fig. 1 Transverse cross section of proposed H-PCF where, Λ=0.91μm, $d_1/\Lambda=0.83$, $d_2/\Lambda=0.95$, $d_3/\Lambda=0.9$, $d_4/\Lambda=0.5$ and for elliptical air holes $a_1/\Lambda=0.83$ & $b_1/\Lambda=0.91$, $a_2/\Lambda=0.36$ & $b_2/\Lambda=0.91$.

3. NUMERICAL MODEL

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. The wavelength-dependent refractive index of the silica is included in the simulation from Sellmeier equation. Chromatic dispersion $D(\lambda)$, confinement loss L_c and birefringence B can be calculated by the following equations [14].

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

$$L_c = 8.686 \times k_0 \mathrm{Im}[n_{eff}] \times 10^3 dB/km$$

$$B = |n_x - n_y|$$

where, Re[n_{eff}] is the real part of refractive index n_{eff} and Im[n_{eff}] imaginary part of effective refractive index n_{eff}, λ is the wavelength in vacuum, c is the light velocity in vacuum and k_0 is the free space wave number.

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 the electric field amplitude in the medium. 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 wavelength dependence of dispersion of the proposed design for y polarized mode with optimum design parameters. In our study, we set pitch, Λ=0.91μm, d_1/Λ =0.83, d_2/Λ=0.95, d_3/Λ=0.9, d_4/Λ=0.5 and for elliptical air holes a_1/Λ =0.83 & b_1/Λ=0.91, a_2/Λ =0.36 & b_2/Λ=0.91. Fig. 2 also exposes the effect by varying global diameter of pitch Λ, ± 1% to ± 2%, while other parameters are kept constant. In PCF during fabrication ± 1% variation in global diameters may be occurred [21]. By considering fabrication difficulty, we have discussed the effect on dispersion and birefringence 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.

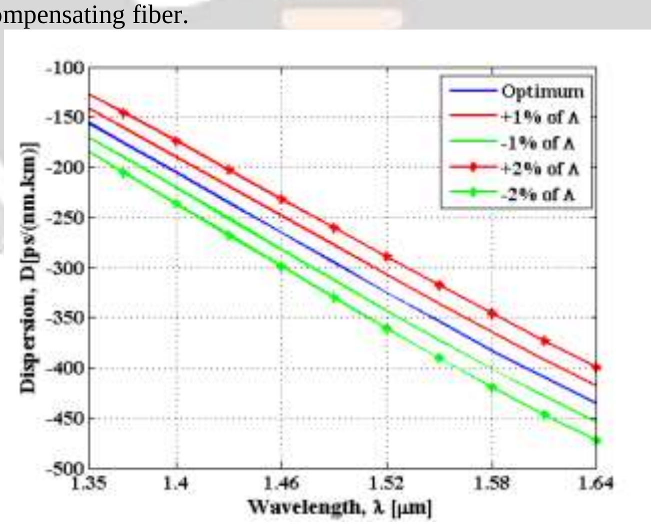


Fig. 2 (a) Wavelength dependence dispersion curve for y polarization

Birefringence characteristics of the proposed ultra high PCF are also shown in fig. 3. From figure it is seen that this proposed PCF shows birefringence about 2.962×10^{-2} at excitation wavelength 1550 nm. As the core designed asymmetrically, the proposed design reveals ultra high birefringence, which is essential in polarization maintaining applications. As pitch is varied as ± 1% to ± 2% from optimum value, birefringence at 1550 nm becomes 0.02885, 0.02934, 0.03001 and 0.03039 respectively.

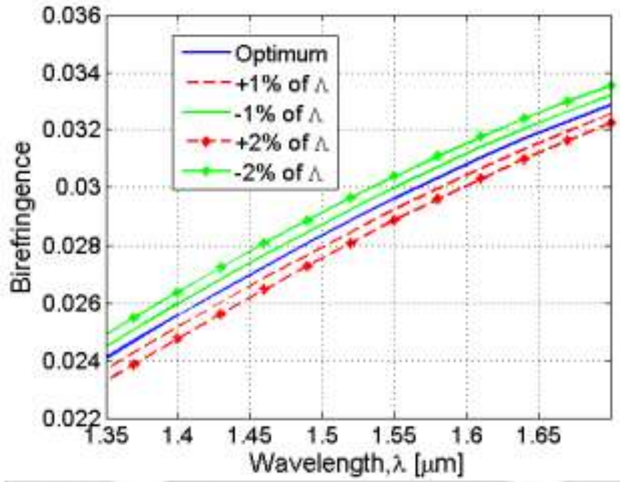
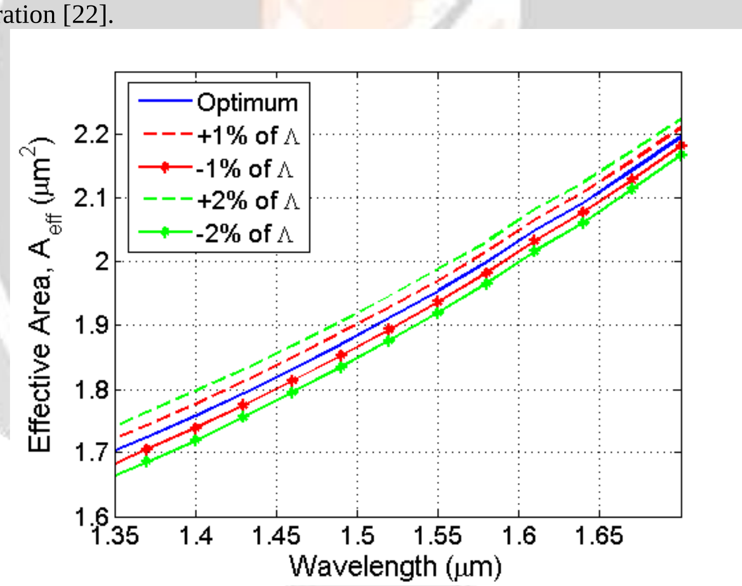
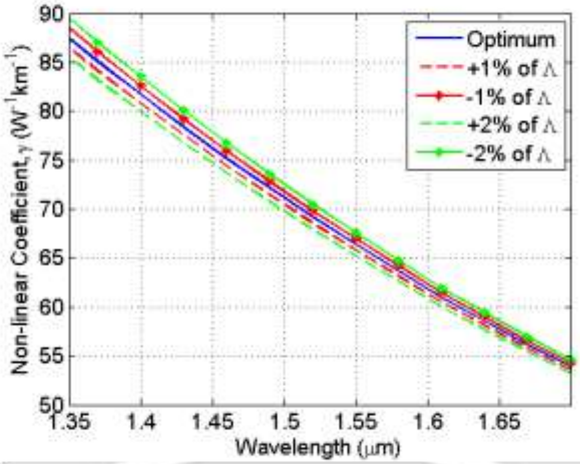


Fig. 3 Birefringence as function of wavelength by varying pitch value.

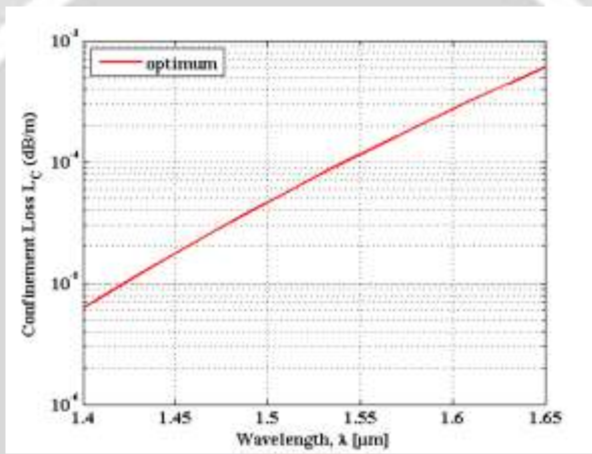
From Fig. 4(a) it is understood that our proposed PCF exhibits small effective mode area which is well enough for obtaining large nonlinearity. The optimum value of effective mode area of the proposed H-PCF is 1.955μm^2 at excitation wavelength 1550 nm. Fig. 4(b) shows the nonlinearity vs wavelength 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)



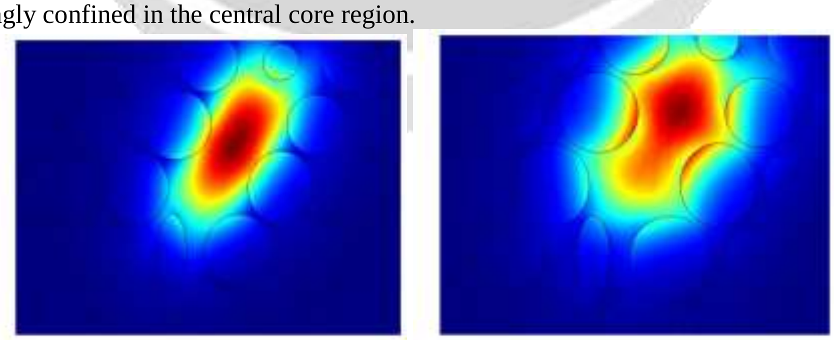
(b)



(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) curves as a function of wavelength. The optimum value of confinement loss at 1550 nm wavelength is in the order of 10^{-5}. 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 Field distributions of fundamental modes 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 the excitation wavelength of 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 properties of the proposed PCF and other PCFs at 1550 nm is shown in Table I.

TABLE I: Comparison of Modal Properties Between proposed PCF and Other Designs

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 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 for sensing applications and large value of negative dispersion in the broadband telecommunication band. The designed PCF offers high birefringence of 2.962×10-2 at the operating wavelength of 1550 nm which makes it an eligible candidate for sensing applications. Another excellent feature of our designed fiber is that it offers negative dispersion coefficient of about -354.3 ps/(nm.km) and high nonlinearity of about 66.36 W-1km-1 simultaneously. Moreover, the proposed PCF has circular air holes in the fiber cladding that simplify the fabrication process Due to having outstanding guiding properties, our proposed PCF could be a suitable contender for sensing applications, super-continuum generator and dispersion compensation in broadband high bit rate transmission network.

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