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High Birefringent Photonic Crystal Fiber with Large Nonlinearity for Sensing Applications

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Abstract— A hexagonal microstructure photonic crystal fiber (PCF) is introduced in this paper exhibiting ultra-high birefringence property with ultra low confinement loss for sensing application. The guiding properties are defined applying finite element method. An ultra high birefringence of 2.105×10^{-2} at operating wavelength of 1550nm is simulated. The proposed PCF also offers large value of negative dispersion coefficient of – 327.4 ps/(nm.km), large value of nonlinear coefficient of 82.53 $W^{-1}km^{-1}$, 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.

Index Terms— Photonic crystal fiber, Nonlinear coefficient, Ultra-high birefringence.

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1. Introduction

Currently it has been an eye catching phenomena that the photonic crystal fibers (PCFs) have drawn the attention taking an important acceptance of researchers because of their phenomenal attributes which is actually including high birefringence, large nonlinearity and large negative value of dispersion due to the introduction of greater freedom in design parameter in comparison with ordinary optical fiber. There is a considerable number of research papers on photonic crystal fiber for the application of sensing and high bit rate communication system has been proclaimed in the recent time. It is to state that, birefringence is one of the most alluring appearance among the characterstics of PCFs. Because of a large index difference and design resilience in photonic crystal fibers it would be relatively easier to procure high birefringence. Until now, a remarkable number of layouts of highly birefringent PCFs have been published [1-15]. Different types of air holes arrangement in the core as well as cladding is proposed in order to achieve ultra high birefringence. A high birefringence of 8.7×10^{-3}, photonic crystal fiber (PCF) applying the complex unit cells in cladding is proposed by Yang et. al [9].

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This paper represents the proposal of hexagonal photonic crystal fiber with circular air-holes in the fiber cladding clarifies the fabrication process. The chief advantage of this proposed framework is the docility of design and also counts the ultra high birefringence and large nonlinearity for sensing applications. The proposition of photonic crystal fiber also endeavours large value of negative dispersion which is pretty conclusive for high-bit-rate transmission network. Another enhancement of this proposed PCF is to attenuate the intricacies of fabrication process where circular air holes in the cladding region and elliptical air holes in 1st ring of PCF are used. According to simulations, the designed PCF illustrates ultra high birefringence of 2.105×10^{-2} and large negative dispersion of – 327.4 ps/(nm.km) at the operating wavelength of 1550 nm.

2. Design Methodology

In fig. 1, the air holes distribution of the proposed photonic crystal fiber consists of five air hole layers. The circular air holes are accommodated in the second, third, fourth and fifth layers whereas the first layer holds the elliptical and semicircular air holes. The aim of using semicircular and elliptical air holes is to increase the ultrahigh birefringence and large nonlinearity. The proposed PCF contains five rings where the air holes diameters of the fourth ring are relatively smaller than the rest of the four air hole rings. Here silica is playing an important role in this proposed structure since it has been a dominant material and the air holes are organized in such a manner so that it takes a shape of a hexagon. In order to strengthen the value of 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 $a_1/\Lambda=0.255$ & $b_1/\Lambda=0.91$ and the rest of the four semicircular air holes diameter are about $d_3/\Lambda=0.91$, $d_4/\Lambda=0.85$. The negative dispersion characteristics is achieved because of the value of pitch Λ=0.91µm. The refractive index of fiber silica is 1.45 and refractive index of air-hole is 1.

3. Numerical Method

In order to analyse the properties of the proposed hexagonal photonic crustal fiber, Finite element method (FEM) is a. Carrying out the numerical simulation circular perfectly matched layers (PML) boundary condition is applied. For figuring out the confinement loss, dispersion and birefringence commercial full-vector finite-element software (COMSOL) 4.2 is used. The background material of our proposed hexagonal PCF is silica whose refractive index has been established with the aid of

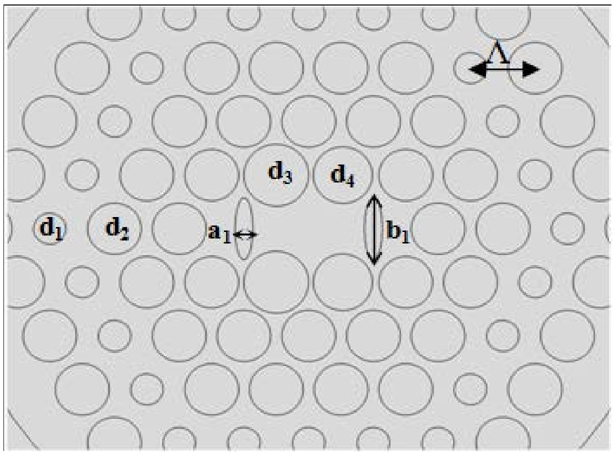


Fig. 1. Transverse cross section of proposed H-PCF where, Λ =0.91μm, d_1/ Λ =0.5, d_2/ Λ =0.83, d_3/ Λ =0.91, d_4/ Λ =0.85 and for elliptical air holes a_1/ Λ =0.255 & b_1/ Λ =0.91.

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

$$D(\lambda) = -\lambda / c(d^2 \,\mathrm{Re}[n_{eff}] / d\lambda^2) \quad (1)$$

$$L_c = 8.686 \times k_0 \mathrm{Im}[n_{eff}] \times 10^3 \, dB/km \quad (2)$$

$$B = |n_x - n_y| \quad (3)$$

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]:

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

where, A_{eff} is the effective mode area in μm² 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

$$\gamma = (\frac{2\pi}{\lambda})(\frac{n_2}{A_{eff}}) \quad (5)$$

4. Simulation Results and Discussion

Fig. 2 displays 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 =0.5, d_2/ Λ =0.83, d_3/ Λ =0.91, d_4/ Λ =0.85 and for elliptical air holes a_1/ Λ =0.255 & b_1/ 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 – 327.4 ps/(nm.km) is obtained at excitation wavelength 1550nm which is well enough for the application of dispersion compensating fiber.

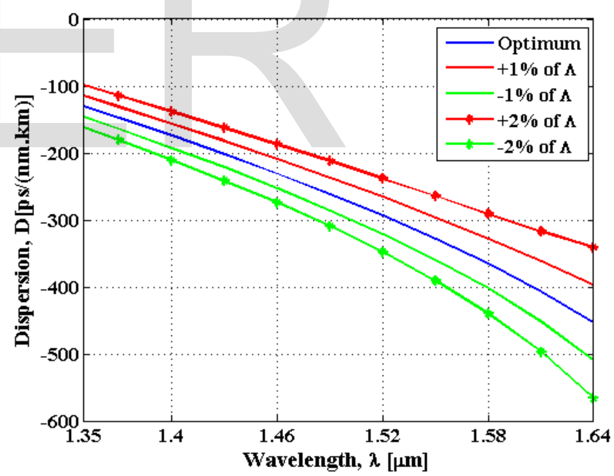
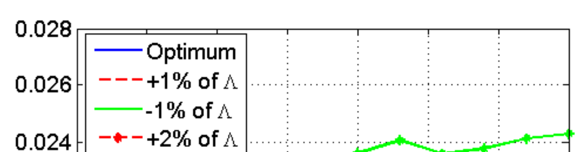


Fig. 2. Wavelength dependence dispersion curve for y polarization.

In fig. 3 the features of birefringence of the proposed ultra high PCF are also visible. It is reflected from the figure that this proposed PCF shows birefringence about 2.105×10⁻² at excitation wavelength 1550 nm. As the core is designed asymmetrically, the proposed design unveils ultra high birefringence, which is required in polarization maintaining applications. As pitch is varied as ± 1% to ± 2% from optimum value, birefringence at 1550 nm becomes 0.01977, 0.0223, 0.0185 and 0.0236 respectively.



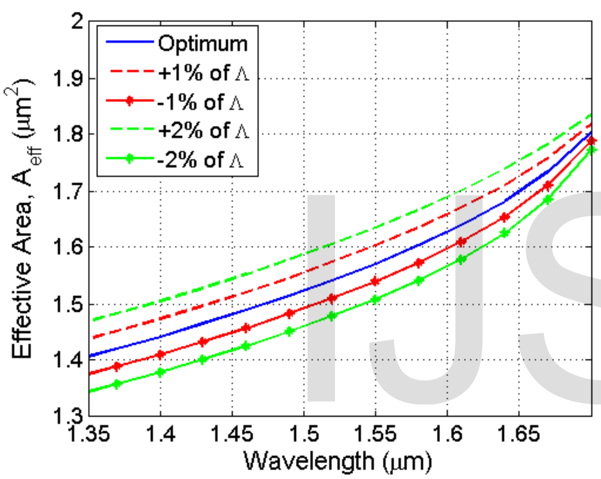


Fig. 4(a). Wavelength dependence effective area.

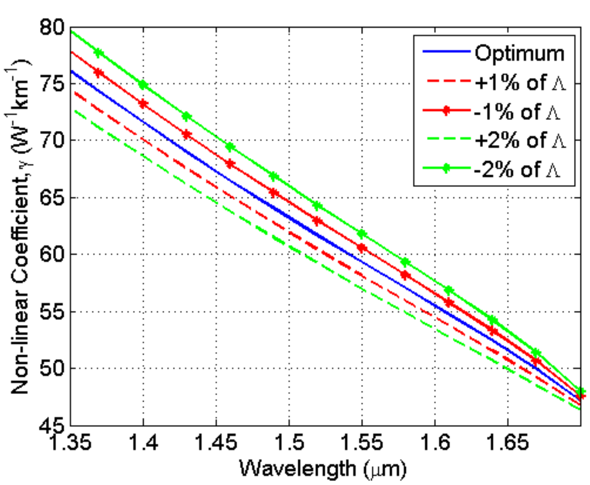


Fig. 4(b). Wavelength dependence nonlinear coefficient.

From Fig. 4(a) it is perceived that the proposed PCF explains small effective mode area which is well enough for achieving large nonlinearity. Ideally the value of effective mode area of the proposed H-PCF is 1.572 μm² 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 82.53 $W^{-1}km^{-1}$ at 1550 nm wavelength. The value of large nonlinear coefficient is remarkably well enough for the application of sensing and super-continuum generation [22].

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.

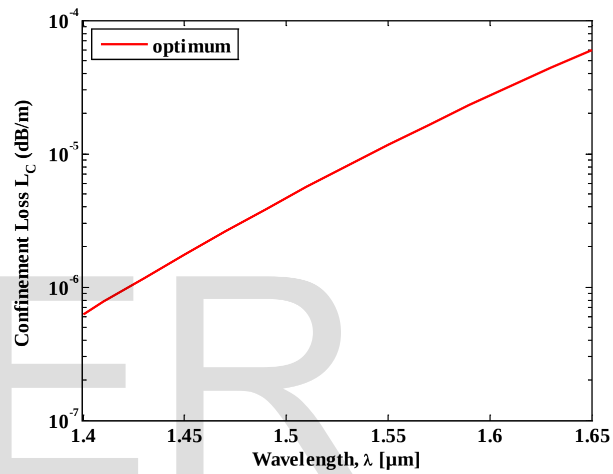


Fig. 4(c). Wavelength dependence confinement loss.

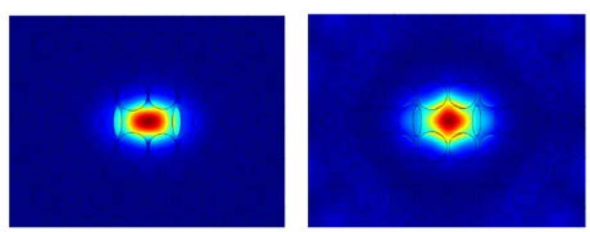


Fig. 5. Field distributions of fundamental modes at 1550 nm for (a) x-polarization and (b) y-polarization.

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.

PCFs	Comparison of modal properties			
	D(λ) *Ps/(nm.km)*	**B=|n_x–n_y|**	**A_{eff} (μm²)**	**γ ($W^{-1}km^{-1}$)**
Ref. [9]	-------	1.83×10^{-2}	------	
Ref. [11]	-300	------	1.55	83.67
Ref. [13]	-588	1.81×10^{-2}	3.41	------
Ref. [15]	-474.5	------	1.60	------
Ref. [23]	----------	1.75×10^{-2}	3.248	
Ref. [24]	-----------	2.62×10^{-2}	-----	------
Proposed H-PCF	-327.4	2.105×10^{-2}	1.572	82.53

5. Conclusions

In conclusion, the proposed hexagonal microstructure photonic crystal fiber (PCF) ensures ultrahigh birefringence for sensing applications at the same time it verifies the large value of negative dispersion in the broadband telecommunication band. The reperesentation of the PCF affords a high birefringence of 2.105×10^{-2} at the operating wavelength of 1550 nm which makes it an eligible candidate for sensing applications. Another important feature of the designed fiber is that it offers negative dispersion coefficient of about -327.4 ps/(nm.km) and high nonlinearity of about 82.53 $W^{-1}km^{-1}$ 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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