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Proposal for Ultra-high Birefringent Photonic Crystal Fiber with Ultra-low Confinement Loss, Large Negative Dispersion and Large Nonlinearity

Md.Ishtiaq Hasan[1], Md.Aseer Awsaf[1], Md.Nafiz Ahbabur Rahman[1], Md.Iqbal Hossain Abdullah[1], Mohammad Mahmudul Alam Mia[2] and Shovasis Kumar Biswas[1]

[1]*Department of Electrical & Electronic Engineering, Independent University, Bangladesh.*
[2]*Department of Electronics & Communication Engineering, Sylhet International University, Sylhet, Bangladesh.*
Corresponding Author's Email Address: biswassk@iub.edu.bd

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ABSTRACT

This paper presents a hexagonal microstructure photonic crystal fiber (PCF) which provides ultra-high birefringence property with ultra low confinement loss and large nonlinearity for sensing application. Finite element method is used as a numerical simulation tool to characterize the properties of the proposed PCF. Based on our result, we found ultra high birefringence of 2.957×10-2 at operating wavelength of 1550nm from the numerical simulation. The proposed PCF also offers large value of negative dispersion coefficient of -517.6 ps/(nm.km). It also offers large value of nonlinear coefficient of 70.73 W-1km-1 and ultra low confinement loss in order of 10-6at excitation wavelength 1550nm. These reported results can be widely used for the broadband dispersion compensation in high-bit-rate transmission networks and sensing.

Keywords: Photonic crystal fiber (PCF), Ultra-high birefringence and Nonlinear coefficient.

1. INTRODUCTION

Now a days a great number of research are done in the field of photonic crystal fiber because they have high birefringence, large negative value of dispersion and large nonlinearity for its pliable design framework contrast to usual optical fiber. For the application of sensing and high bit rate transmission property of the photonic crystal fiber, a huge number of research papers are issued at present [1-11]. Birefringence is one of the fascinating features of the photonic crystal fiber. Due to its design flexibility and large index difference, high birefringence can be easily obtained. A number of high birefringence PCFs have been described up to this point. Different types of air holes order in the core as well as cladding are suggested to get ultra high birefringence. Using the complex unit cell in cladding region, Wang et. Al have suggested a high birefringence of 1.83×10^{-2} PCF [9].

Several groups have taken their own strategy to get ultra high birefringence and large negative dispersion. An octagonal MOF have suggested in [10] which shows high birefringence of 1.67×10^{-2} and large value of negative dispersion of 239.5 ps/(nm.km). Other group have suggested a high negative value of dispersion 300 ps/(nm.km) without considering the birefringence. A new formation that covers all three communication band is outlined by Mastsui et al. But it has less dispersion value that's why it needs large fiber for dispersion compensation [12].

In addition ultra high birefringence photonic crystal fibers with large nonlinearity have received current attention in sensing and super continuum (SC) implementation. The well – preserved polarization state along with the fiber is an expected characteristic for SC generation, as low power is needed for enhanced nonlinear interaction [13]. In our proposal, we suggest hexagonal photonic crystal fiber having circular air-holes in the fiber cladding which makes easier the fabrication process. Design flexibility along with ultra high birefringence and large nonlinearity for sensing applications are the major advantages of our proposed structure. Our proposed structure also offers large value of negative dispersion which is very decisive for high bit rate communication network. Our proposed structure eliminates the complexity of the design procedure because circular air holes in the cladding region and elliptical air holes are used in the 1st ring of PCF. From the simulation our proposed PCF exhibits ultra high birefringence of 2.957×10^{-2} and large negative dispersion of -517.6 ps/(nm.km) at the excitation wavelength of 1550 nm.

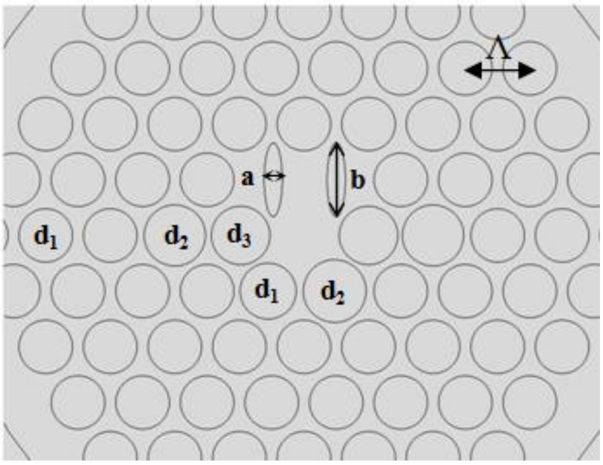


Fig. 1 Transverse cross section of proposed H-PCF where, Λ=0.91µm, d_1/Λ =0.83, d_2/Λ=0.9, d_3/Λ=0.85 and for elliptical air holes a/Λ =0.26 & b/Λ=1.

2. DESIGN METHODOLOGY

The proposed photonic crystal fiber contains five air hole layers showed in the figure-1. The first layer consists of elliptical and semicircular air holes. The 2nd, 3rd, 4th and 5th layer consist of circular air holes. To achieve ultra high birefringence and large nonlinearity the semicircular and the elliptical air holes are used. In our proposed PCF, among the five rings three rings are equal in diameter indicated by d_1. The air holes are organized in hexagonal shape and for that silica material is used. To obtain high birefringence four air hole 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/ Λ =0.26 & b/ Λ=1 and the rest of the four semicircular air holes diameter are about d_1/ Λ =0.83, d_2/ Λ=0.9, and d_3/ Λ=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

Finite element method is used to explore the properties of our proposed hexagonal photonic crystal fiber. Circular perfectly matched layers boundary condition is applied to investigate the guiding characteristics of our proposed ultra high birefringence photonic crystal fiber. To compute the confinement loss, dispersion and birefringence commercial full-vector finite-element software (COMSOL) 4.2 is used. Silica is used as context material whose refractive index has been obtained by using well known Sellmeier formula. From the Sellmeier equation wavelength dependent refractive index is persuaded in the simulation. Chromatic dispersion *D(λ)*, confinement loss L_c and birefringence *B* can be calculated by the following equations [14].

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

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

$$B = |n_x - n_y|$$

Hence, Re[n_{eff}] is the real part of refractive index n_{eff} and $\mathrm{Im[n_{eff}]}$ 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]:

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

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 confine in a small area. Nonlinearity in a photonic crystal fiber is defined as follows

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

4. Simulation results and discussion

The wavelength dependence dispersion of the proposed design for y polarized mode with ideal design parameters are shown in fig. 2. In our design, we set pitch, Λ=0.91μm, d_1/ Λ =0.83, d_2/ Λ=0.9, d_3/ Λ=0.85 and for elliptical air holes a/ Λ =0.26 & b/ Λ=1. Fig. 2 reveals the outcome by varying global diameter of pitch Λ, ± 1% to ± 2%, while other parameters are kept constant. ± 1% deviation in global diameters may be occurred during the fabrication of the PCF [21]. Considering the complication of the fabrication process, we have discussed the outcome on dispersion and birefringence by altering pitch value ± 1% to ± 2%. The optimum value of negative dispersion of – 517.6 ps/(nm.km) is acquired at excitation wavelength 1550nm which is sufficient for the application of dispersion compensating fiber.

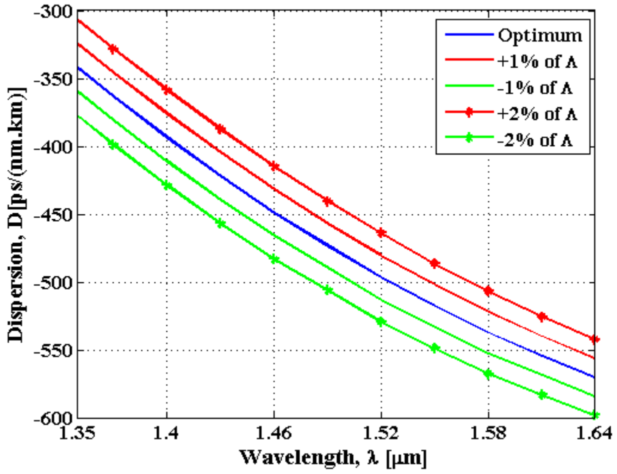


Fig.2 Wavelength dependence dispersion curve for y polarization

In figure 3 the birefringence features are shown. Our proposed PCF shows that the birefringence is about 2.957×10^{-2} at excitation wavelength 1550nm which is shown in fig.3. As the core designed lopsided proposed design exhibits ultra high birefringence, this is necessary in polarization maintaining applications. As pitch is varied as ± 1% to ± 2% from optimum value, birefringence at 1550 nm becomes 0.02929, 0.02984, 0.02901 and 0.03012 respectively.

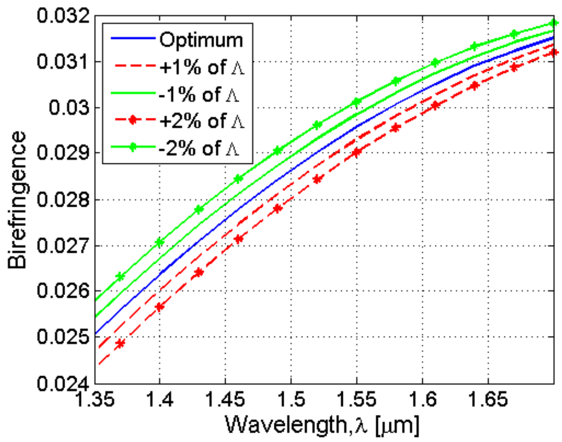
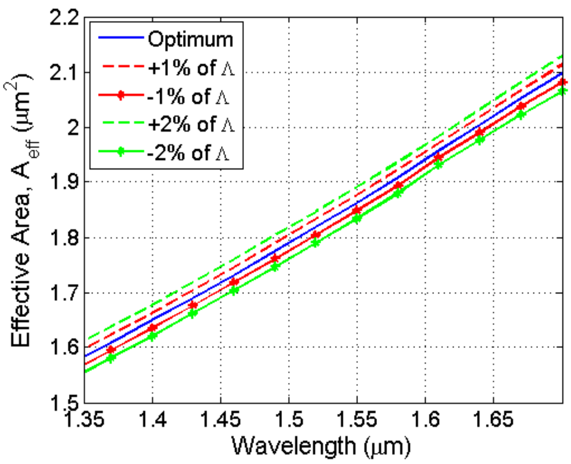
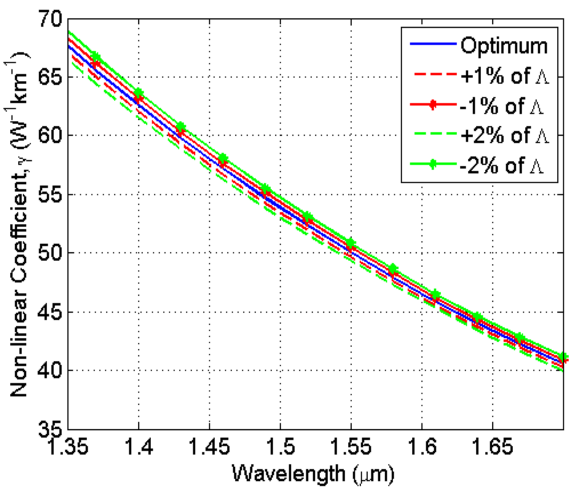


Fig. 3 Birefringence as function of wavelength by varying pitch value.

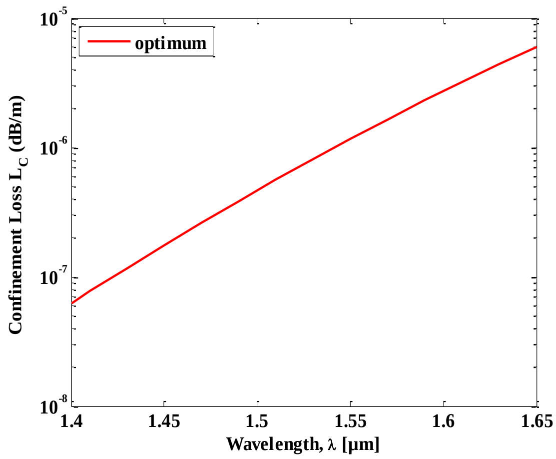
It is acknowledged that our suggested PCF exhibits small effective mode area which is good enough for getting large nonlinearity which is clearly shown in fig.4 (a). The optimum value of effective mode area of the proposed H-PCF is 1.863 μm^2 at excitation wavelength 1550 nm. It is indicated in Fig. 4(b) that the nonlinearity vs wavelength for optimum design parameter and pitch variation from ± 1% to ± 2%. The value of nonlinear coefficient is 70.73 $W^{-1}km^{-1}$ at 1550 nm wavelength. The value of large nonlinear coefficient is sufficient for the application of sensing and super-continuum generation [22].



(a)



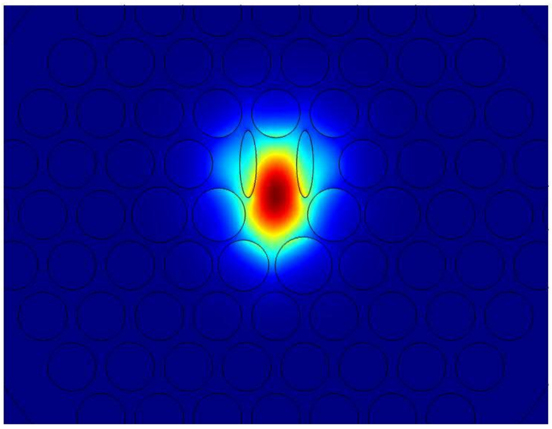
(b)



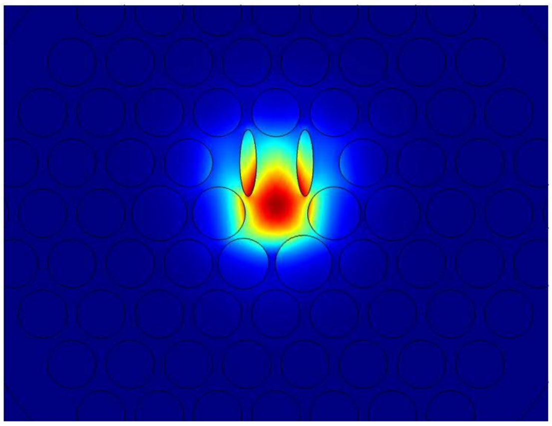
(c)

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

Fig. 4 (c) curves shows that the optimum value of confinement loss of our proposed ultra high birefringence PCF is a function of wavelength. The optimum value of confinement loss at 1550 nm wavelength is in the order of 10^{-6}. Ultra low confinement loss as contrast with ordinary fiber is the main outcome of our proposed PCF. So light is strongly restricted 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.

The optical field profile for x and y polarization modes at the excitation wavelength of 1550 nm are shown in the Fig.5. Numerical simulation says 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.

Finally, a comparison is made between properties of the proposed PCF and some other fibers. Table 1 compares those fibers taking into account the dispersion magnitude, birefringent, effective area. All values are taken at 1550 nm. It should be pointed out that the PCF [13] has low dispersion coefficient as compared with the proposed structure but the proposed PCF shows ultra high birefringence and large nonlinearity than in Ref. [13]. Similarly, effective area, A_{eff} of Ref. [11] and [21] is better than Proposed H-PCF but other geometrical properties such as birefringence and dispersion is much better than Ref. [11, 21]. So, the proposed H-PCF requires a small fiber to compensate a SMF.

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

PCFs	Comparison of modal properties		
	Dispersion, D(λ) Ps/(nm.km)	**Birefringence, B=|n_x–n_y|**	**Effective area, 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	-517.6	2.957×10^{-2}	1.863

5. Conclusion

In conclusion, a high birefringent index-guiding hexagonal microstructure photonic crystal fiber with asymmetric core-cladding region is successfully proposed that simultaneously ensures ultrahigh birefringence for sensing applications and large value of negative dispersion in the broadband high bit rate transmission network. The proposed design offer high birefringence of 2.957×10^{-2} at the operating wavelength of 1550 nm. This proposed design also provides nonlinearity of about 70.73 $W^{-1}km^{-1}$ and negative dispersion coefficient of about -517.6 ps/(nm.km) consequently. Besides these, circular air holes in the fiber cladding are proposed that make easier the fabrication process. Due to having outstanding leading qualities, the proposed PCF could be a suitable candidate for sensing applications, super-continuum generation and dispersion compensation in broadband high bit rate transmission network.

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