Asian Journal of Applied Science and Technology (AJAST)
Volume 1, Issue 8, Pages 147-151, September 2017

# Design and Analysis of Hexagonal Photonic Crystal Fiber with Ultra-high Birefringent and Large Negative Dispersion Coefficient for the Application of Sensing and Broadband Dispersion Compensating Fiber

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*Article Received: 07 August 2017* *Article Accepted: 19 September 2017* *Article Published: 25 September 2017*

ABSTRACT

A hexagonal microstructure photonic crystal fiber (PCF) with circular air holes in the fiber cladding and elliptical air holes in the fiber core is proposed which gives ultra high birefringence and very low confinement loss for sensing application. To characterize the modal properties of the proposed photonic crystal fiber, finite element method is used. The proposed PCF exhibits ultra high birefringence of 3.34×10-2 at operating wavelength 1550nm by using simulation software COMSOL multiphysics. Our proposed PCF gives large value of nonlinear coefficient of 63.51 W-1km-1, large value of negative dispersion coefficient of -566.6 ps/(nm.km), and also ultra low confinement loss which is in the order of 10-7at excitation wavelength 1550nm.

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

## 1. INTRODUCTION

Nowadays the researchers are very interested in photonic crystal fibers (PCFs) because of their remarkable characteristics such as large nonlinearity, high birefringence and large negative value of dispersion, because its design parameter is flexible than ordinary optical fiber. Recently for the application of sensing and high bit rate communication system lots of research paper are published [1-11]. Birefringence is one of the most interesting characteristics among the features of PCFs. By getting large index difference and flexible photonic crystal fibers design high birefringence can easily establish. Up to now, various designs of highly birefringent PCFs have been reported. Different types of air hole arrangement in the core as well as cladding are presented for achieving ultra- high birefringence. A high birefringence of $1.83\times10^{-2}$, by using the complex unit cells in cladding the photonic crystal fiber (PCF) has been proposed by Wang et.al [9].

So many attempts have been taken to achieve ultra- high birefringence and large negative dispersion by different groups. With the high birefringence of $1.67\times10^{-2}$ and large value of negative dispersion of -239.5 ps/(nm.km) an octagonal MOF have been offered. Another group also offered a new PCF structure with large value of negative dispersion of -300 ps/(nm.km) without considering birefringence. A new design which covers all three communication band designed by Matusi et al. but it needs large fiber for dispersion compensation because of its low dispersion value [12]. Besides in sensing and application of super-continuum (SC) ultra-high birefringence photonic crystal fibers including large nonlinearity have drawn a very good awareness. For SC generation along with the fiber the well-preserved polarization is an exceptional feature because to enhance nonlinear interaction less power is needed [13].

This paper offers hexagonal photonic crystal fiber which has circular air-holes in the fiber cladding which cause simplification of the fabrication process. Our proposed structure leads in the design flexibility accompanying ultra-high birefringence and large nonlinearity for sensing application.

The photonic crystal fiber we offered has a large negative dispersion value, which is very significant for high-bit-rate communication network. Also in our proposed PCF we have used circular air holes in the cladding region to make less complexity of fabrication process. After simulating we found, The PCF presents ultra-high birefringence of $3.34\times10^{-2}$ and large negative dispersion of -566.6 ps/(nm.km) at excitation wavelength 1550 nm.

## 2. DESIGN METHODOLOGY

In fig. 1 the proposed photonic crystal fiber air hole distribution contains five air hole layers. First layer made up with elliptical and semicircular air holes and second, third, fourth and fifth layers made up with circular air holes. To obtain ultrahigh birefringence and large nonlinearity semicircular and elliptical air holes is used. The diameters of air holes of three rings are equal expressed by $d_1$ in the proposed PCF which consists of five rings. In our proposed design we used silica as a principle material and air holes are sorted in hexagonal shape. Six air holes in first ring along the y axis construct in elliptical shape to get high birefringence. Major axis of elliptical air holes are denoted as $a_1/\Lambda=0.26$, $a_2/\Lambda=0.83$, and minor axis of six elliptical air holes are denoted as $b_1/\Lambda=1$ & $b_2/\Lambda=0.91$. We get negative characteristic of dispersion because of pitch value is $\Lambda=0.91\mu m$. To improve the birefringence property all elliptical air holes are used at the core region. Fiber silica's refractive index is 1.45 and air hole's refractive index is 1.

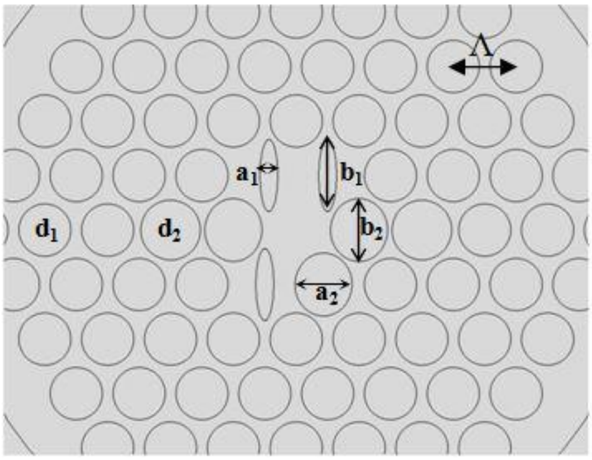



Fig. 1 Transverse cross section of proposed H-PCF where, Λ=0.91µm, $d_1$/ Λ =0.83, $d_2$/ Λ=0.95, for elliptical air holes $a_1$/ Λ =0.26 & $b_1$/ Λ=1, $a_2$/ Λ =0.83 & $b_2$/ Λ=0.91.

## 3. Numerical method

To investigate of our proposed hexagonal photonic crystal fiber properties we used finite element method (FEM). Boundary condition of circular perfectly matched layers (PML) is used to achieve the numerical simulation. We used COMSOL- Commercial full-vector finite-element software 4.2 to determine the birefringence, confinement loss and dispersion properties of our proposed PCF. By using Sellmeier equation the refractive index of silica can be obtained. We used silica as our background material in our offered hexagonal PCF. Chromatic dispersion *D(λ)*, confinement loss $L_c$ and birefringence *B* can be determined by the given equations [14].

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

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

$$B = |n_x - n_y|$$

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

In the below the effective mode area $A_{eff}$ is established [15]:

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

Here, the effective mode area $A_{eff}$ in $\mu m^2$ and electric field amplitude is E in the medium. For studying nonlinear case of optical fiber, microcavity [16-20] and photonic crystal fiber the effective area is very important. Effective mode area is defined to understand the nonlinear phenomena of photonic crystal fiber. Effective mode area and nonlinearity is inversely proportional to each other i.e light must confine in a short area for better nonlinearity. Photonic crystal fiber nonlinearity can be defined as

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

## 4. Simulation Results and discussion

The In fig.2 we can see wavelength is depending on dispersion for y polarized mode with optimum design parameters of the proposed design. We set pitch, Λ=0.91µm, $d_1$/ Λ =0.83, $d_2$/ Λ=0.95, for elliptical air holes $a_1$/ Λ =0.26 & $b_1$/ Λ=1, $a_2$/ Λ =0.83 & $b_2$/ Λ=0.91, in our proposed PCF. In fig.2 we also can see the figure is effected by the variation of global diameter of pitch Λ, ± 1% to ± 2% while other parameters are kept constant. During fabrication ± 1% variation in global

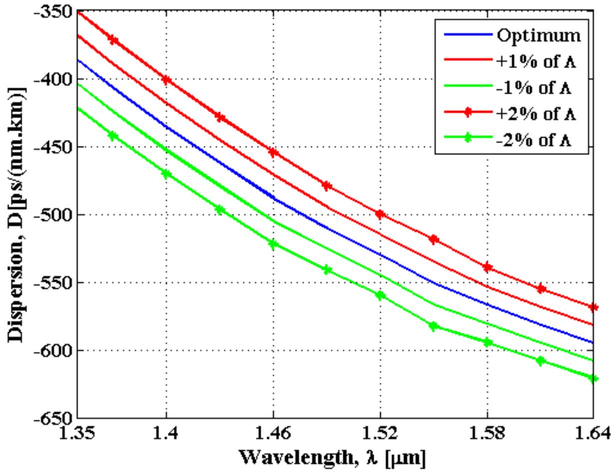



Fig. 2 Wavelength dependence dispersion curve for y polarization

diameters may be occurred in PCF [21]. With the consideration of difficulty of fabrication, we analyzed the dispersion effect and birefringence with changing of pitch value from ± 1% to ± 2%. The optimum value of negative dispersion is -566.6 ps/(nm.km) at excitation wavelength 1550nm.

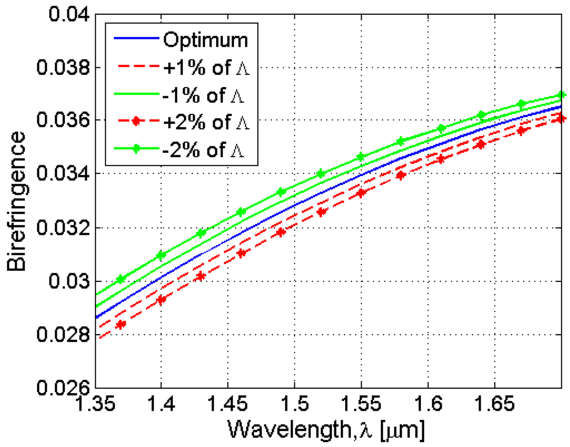
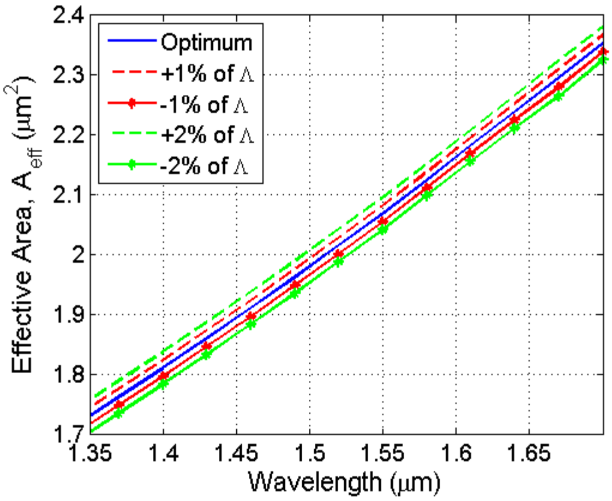
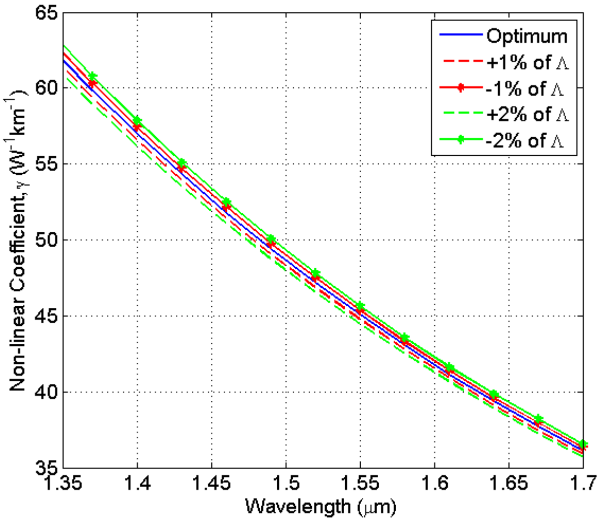



Fig. 3 Birefringence as function of wavelength by varying pitch value.

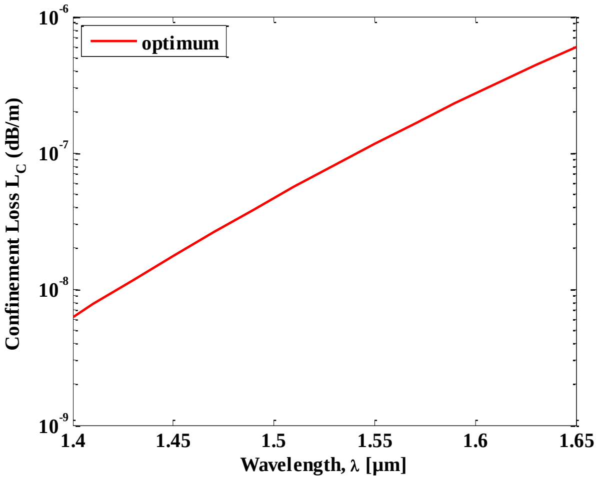
Fig.3 shows the ultra high birefringence characteristics of our proposed design .This figure shows that birefringence about $3.34 \times 10^{-2}$ at excitation wavelength 1550 nm. The presented design reveals ultra high birefringence because the asymmetrical design of the core, which is necessary in applications of polarization maintaining. Birefringence at 1550 nm becomes 0.03362, 0.0343, 0.03328 and 0.03464 respectively because the variation of the pitch is ± 1% to ± 2% from ideal value.




(a)




(b)

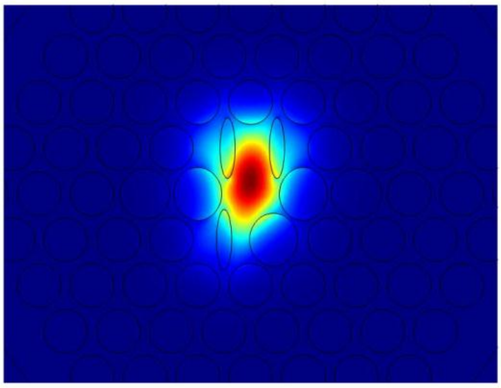



(c)

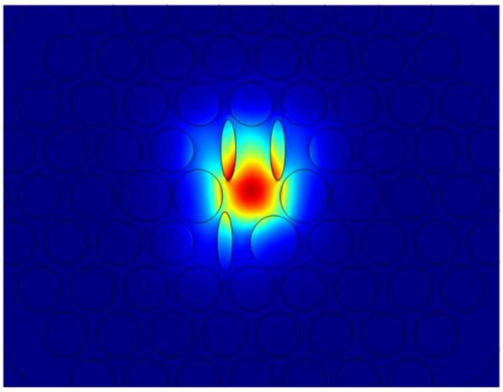
Fig. 4 (a) Wavelength dependence effective area (b) nonlinear coefficient (c) confinement loss curve of proposed H-PCF for optimum design parameters

In fig.4(a) shows that our presented PCF viewing small effective mode area. At excitation wavelength 1550 nm the ideal value of effective mode area of the presented H-PCF is 2.069 $\mu m^2$. The nonlinearity vs wavelength for most favorable design parameter in addition with the variation of pitch from ± 1% to ± 2% shows in fig.4(b). At excitation wavelength 1550nm the result of nonlinear coefficient is 63.51 $W^{-1}km^{-1}$ . For the sensing and super continuum generation application large nonlinear coefficient value is very well [22].

The optimum value of confinement loss of our presented ultra high birefringence PCF is shown in fig.4 (c ) as a function of wavelength . At the wavelength of 1550nm the optimum value of confinement loss is $10^{-7}$. With the comparison of ordinary fiber it can easily identify that our presented PCF has excessive low confinement loss. For this reason light is strongly compacted 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.

In fig 5 it is shown that the optical field profile for x and y polarization modes at operating wavelength 1550 nm.

It can be observed that x and y polarized modes are heavily compacted in the center region of the core because of high-index in the region of the core than the region of the cladding in accordance with numerical simulation.

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 | | |
|---|---|---|---|
| | *Dispersion, D(λ) Ps/(nm.km)* | Birefringence, $B=\|n_x – n_y\|$ | Effective area, $A_{eff}$ (μm$^2$) |
| Ref. [9] | ------- | $1.83\times10^{-2}$ | ------ |
| Ref. [11] | -300 | ------ | 1.55 |
| Ref. [13] | -588 | $1.81\times10^{-2}$ | 3.41 |
| Ref. [21] | -474.5 | ------ | 1.60 |
| Ref. [23] | ---------- | $1.75\times10^{-2}$ | 3.248 |
| Ref. [24] | ----------- | $2.62\times10^{-2}$ | ----- |
| Proposed H-PCF | -566.6 | $3.34\times10^{-2}$ | 2.069 |

## 5. Conclusion

To summarize, a hexagonal microstructure photonic crystal fiber (PCF) has been proposed and analysed that simultaneously ensures ultrahigh birefringence for sensing applications and large value of negative dispersion in the broadband telecommunication band. At the operating wavelength of 1550 nm the presented PCF provides modal birefringence of $3.34\times10^{-2}$ with very low confinement loss which is very desirable for the application of sensing. The new proposed PCF also offers large negative dispersion coefficient which is -566.6 ps/(nm.km) and high nonlinearity of 63.51 $W^{-1}km^{-1}$. Additionally, the proposed PCF has circular air holes in the cladding region that clarify the process of fabrication much easier.

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