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Highly Birefringent Wideband Residual Dispersion Compensating Photonic Crystal Fiber

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ABSTRACT: We propose a new type highly birefringent spiral photonic crystal fiber (PCF) for residual dispersion compensation in a wide range of wavelengths. The 2-D finite element method (FEM) with perfectly matched boundary layer (PML) is used for numerical simulation. The arrangement and diameter of circular air holes in the designed PCF has been tuned to offer almost flat dispersion profile with average dispersion coefficients of -609.321601 and -396.32923 ps/nm-km for X and Y-polarization, respectively, within the wavelengths of 1350-1600 and 1350-1800nm. The proposed spiral PCF shows high birefringence of 0.0170 and nonlinear coefficient 44.3679 and 28.1431 $W^{-1}km^{-1}$ for X and Y-polarization at 1550nm.

KEYWORDS: Birefringence, chromatic dispersion, finite element method, non- linear coefficient, spiral PCF.

1 INTRODUCTION

In the recent years, photonic crystal fibers (PCF) compared to conventional optical fiber provides unique features [1] due to freedom in the design of the microstructure cladding around a solid central core where light is guided by means of modified total internal reflection (MTIR). Tailoring ability of the air hole arrangement and its diameter of a PCF has made it to be an attractive optical waveguide in which several important optical properties such as large chromatic dispersion [2-4], large mode area [5], high nonlinearity [6-7] and high birefringence [8-10] can be achieved.

The rapid development of optical fiber network and the boost data rates compels serious residual chromatic dispersion in transmission distances. In addition, optical sources of different wavelengths are being widely used nowadays for optical communication. Hence, the best approach is to nullify the positive chromatic dispersion for a large bandwidth of wavelengths. To serve this, dispersion compensating fiber [11] (DCF), a fiber that contains large negative dispersion properties has to be launched. The chromatic dispersion can be customized by arranging the air hole size, shape and large index contrast of PCF. In recent times, an equiangular spiral photonic crystal fiber (ES-PCF) has been reported [12] for high nonlinearity with ultra flattened dispersion profile and super-continuum generation in the visible region. More recently, effusive technique has been employed [3] to achieve a flattened negative dispersion over E+*S*+*C*+*L*+*U* wavelength bands with an average dispersion 227 ps/nm-km. In order to minimize losses and costs, the dispersion compensation fiber should be as short as possible and thus the magnitude of negative dispersion should be as large as possible in optical fiber communication.

In many applications of PCFs in transmission medium for communication, it is essential to suppress the birefringence to construct the system polarization in sensitive and so polarization states have been maintained using high birefringence PCFs [13]. In the PCF with ideal symmetry [14], the two polarization modes are degenerate. Normally, two methods, breaking the symmetry and built-in- stress can be used to construct high birefringence. To design unsymmetrical, many optimization can be approached, e.g. double or triple defects in the fiber core or the air holes can be elliptical instead of circular one or defected elliptical core with circular air holes. By using these techniques, birefringence up to 10^{-2} has been reported in spiral lattice to form an elliptical core shape [9], elliptical air holes within the fiber [15] or soft glass with crystal core. But we propose index guided spiral PCF with defected elliptical core which serves various potentials such as large flattened negative dispersion, high birefringence and nonlinearity [16]. In particular, nonlinearity can diminish the footprint and power consumption of various optical mechanism.

In this paper, a new spiral PCF with defected elliptical core has been proposed for dispersion compensation fiber. A defected elliptical air hole at the core region is used to achieve a larger negative flattened dispersion to get dispersion compensation over 1350-1600nm for X polarization and 1350-1800nm for Y polarization. Besides this demonstration, an admirable goal would be to take full use of flexibility in design of PCF to take simultaneous wideband high birefringence, large nonlinearity and large negative flattened dispersion, which might be of potential tools in signal processing applications. The factors of the design methodology of the proposed structure are given in Section II. The numerical analysis is explained in Section III, while the conclusions are given in Section IV.

2 Design Methodology

The general structure of the proposed spiral PCF with defected elliptical core in our simulation as illustrated in Fig.1. Compared to the conventional circular lattice structure and hexagonal lattice structure, spiral lattices of circular air holes (black dashed lines) with defected elliptical core in Fig.1 (c), are introduced as the cladding of the PCF. It has 10 arms and the starting air holes of each arm form a single spiral of radius r_o with equal angular displacement from previous one is increased by θ. The radii of subsequent rings are enhanced by geometric progression of following manner (r_o, r_o+p, r_o+2p,…..); where p represents pitch. Each arm contains 16 air holes. Among these, first nine air holes have same radius of r_h. The PCF is composed of elliptical lattices in Fig.1 (b), having 12 circular air holes have same radius of r_e with ellipticity ratio (a: b=2:1) in the central core region, are arranged by Rmamnujan's formula. To make extra large asymmetry, 1 and 7 position air holes are omitted in elliptical core, shown in Fig.1(c). The spiral-shape structure is compact for tight light confinement and large nonlinearity. The defected elliptical arrangement of circular air holes provides high birefringence as well as large negative chromatic dispersion. We use circular air holes to facilitate easy fabrication.

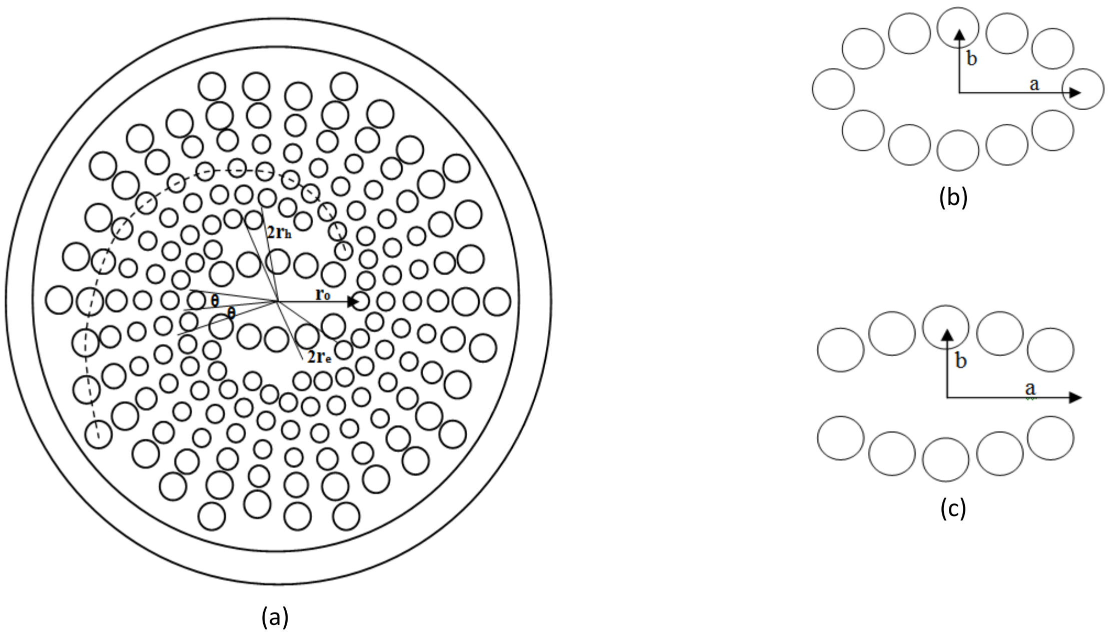


Fig. 1. Cross section of proposed (a) Spiral PCF, (b) elliptical core with circular air holes and (c) defected elliptical core in central region

3 Numerical Analysis

We determine the field distribution and refractive index of the designed spiral PCF with defected elliptical core by using a full-vector finite element method (FEM) software (COMSOL Multiphysics 4.2). The material dispersion of Silica is taken into consideration. The birefringence (Δn_{eff}), chromatic dispersion (D) and nonlinearity (γ) are expressed as follows:

$$\Delta n_{eff} = n_{eff}^{X} \sim n_{eff}^{Y} \quad (1)$$

$$D = -\lambda / c.d^2 n_{eff} / d\lambda^2 \quad (2)$$

$$\gamma = 2\pi n_2 / (\lambda A_{eff}) \quad (3)$$

where c is the light velocity in vacuum, is the wavelength, A_{eff} is the effective area of fundamental mode, and $n_2 = 2.3\times10^{-20} m^2 W^{-1}$ is the nonlinear refractive index of Silica. The material dispersion is considered by using the Sellmeier formula [17] to get the refractive index of silica at different wavelengths. To analyze, r_o = 1.4 μm, ϑ =12°, r_h = 0.154 μm, r_e=0.21 μm, a = 1.3μm and b=0.65μm are reported for the optimized structure. For evaluating the dependency on thickness of perfectly matched layer (PML) has been reported [9]. However, we change the PML value from o.6 to 1.6 μm in shown in Fig.2. It can be clearly seen that the chromatic dispersion remains unchanged with wavelength that would be afforded to fabricate the PCF design easily.

The goal is to generate a flat negative chromatic dispersion of high magnitude over the wide band. Our proposed design shows an average value of chromatic dispersion for X-polarization which is equal to -609.32 ps/(nm-km) with a dispersion variation of 14.26 ps/(nm km) between -598.15 ps/(nm km) and -582.75 ps/(nm-km) in the wavelength range 1350nm to 1600nm which is equal to -396.33 ps/(nm km) for Y-polarization with a dispersion variation of 9.34 ps/(nm km) between -356.25 ps/(nm km) and -388.60 ps/(nm km) in the wavelength range 1350nm to 1800nm. We have compared our result of chromatic dispersion with research articles[3], [18] and [19] that provides better negative dispersion shown in Fig.3.

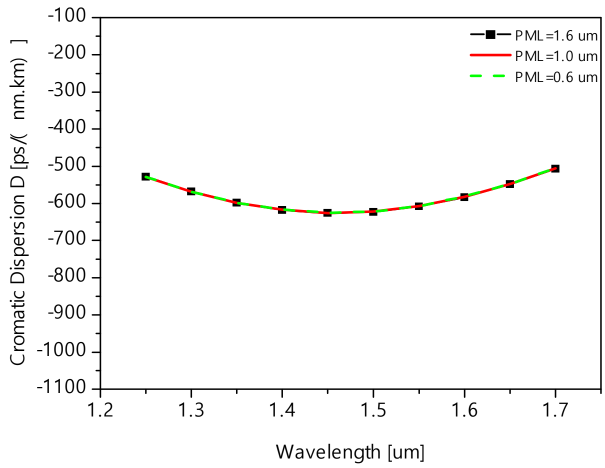


Fig. 2. Dispersion with respect to thickness of PML

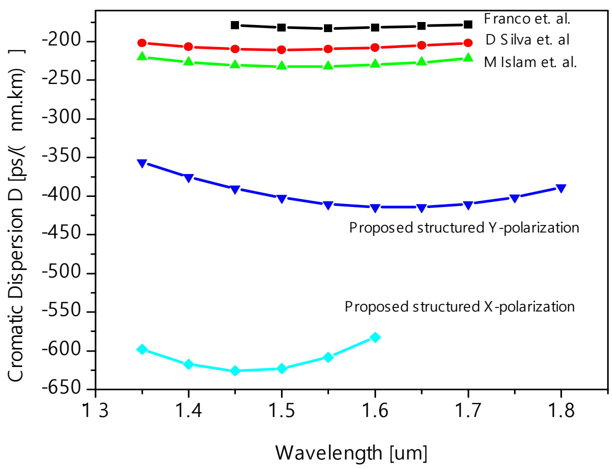
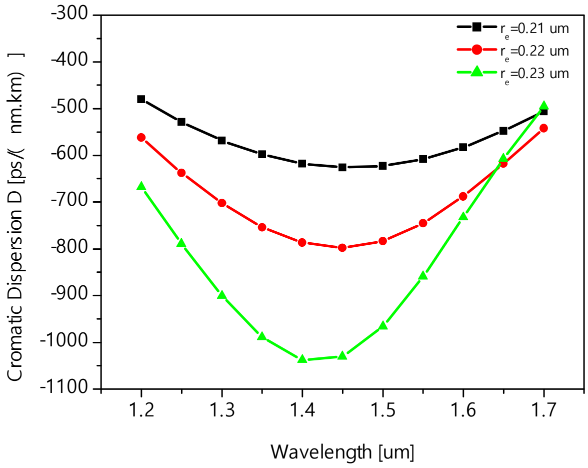


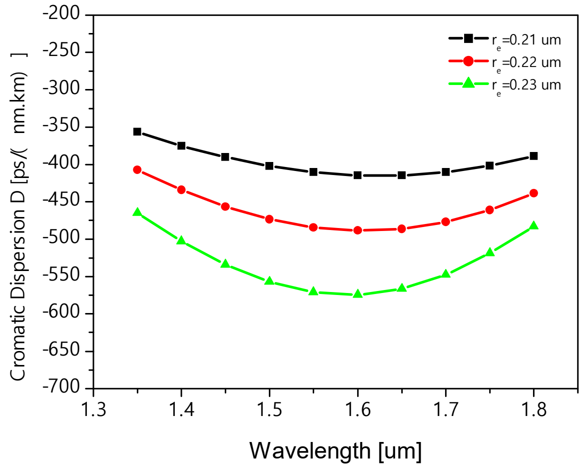
Fig. 3. Comparison between chromatic dispersion

We then investigate the dependence of chromatic dispersion on the wavelength under different re of elliptically circular air holes. With the increase of r_e, dispersion for X and Y polarizations also increases in both case as demonstrated in Fig 4(a) and (b) respectively.

From Fig. 4, it can be explained that 1) negative dispersion for Y-polarization is flatter than X-polarization at r_e equal to 0.21µm and 2) dispersion for X-polarization is varied dramatically which can be achieved up to -1037.49 ps/(nm km) at 1400nm for r_e of 0.23µm and 3) more flatness portion of dispersion is lower than 1550nm (1400nm to 1500nm) for X-polarization which is near to 1550nm and above (1550nm to 1700nm) for Y-polarization. In both cases, variation of flat portion is increased from radius 0.21µm to 0.23µm because field interacts with silica cladding of spiral ring is more for X-polarization (a) than Y-polarization (b) beyond the defected elliptical air holes as illustrated in Fig. 5.

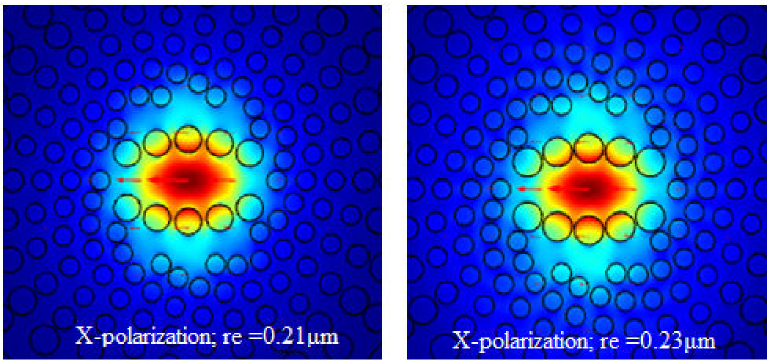


(a)

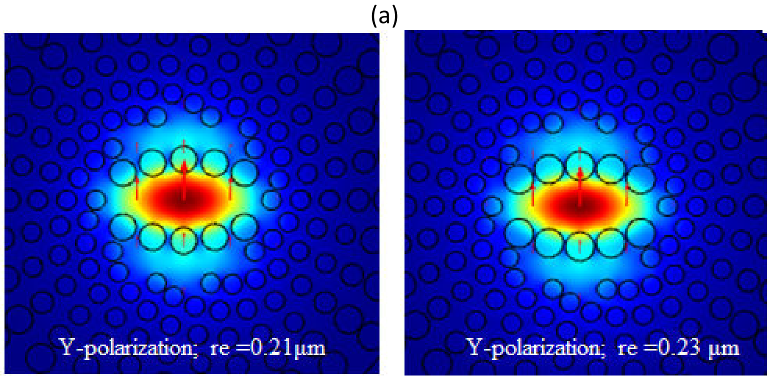


(b)

Fig. 4. ***Chromatic dispersion for (a) X-polarization and (b) Y-polarization***



(a)



(b)

Fig. 5. ***Chromatic dispersion for (a) X-polarization and (b) Y-polarization***

We further examine the dependence of birefringence and non-linearity on the diameter of elliptically circular air holes. After fixing the ellipticity ratio at 2, the birefringence as a function of the diameter of r_e is depicted in Fig.6. The birefringence increases with the increase of the diameter of r_e because the fiber cross-section is more asymmetric. It can be examined that the birefringence is about 0.0170 at 1550nm when r_e=0.21µm. A maximum birefringence of 0.0223 is achieved when r_e enhances up to 0.23µm, manifested in the insets in Fig.6.

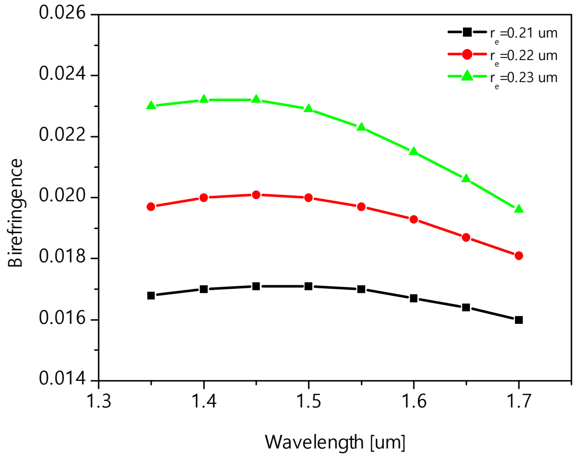


Fig. 6. Birefringence variance with respect to r_e

With the evidence of Fig.7, one can observe that the nonlinear coefficient of our designed PCF is very high, and the nonlinear coefficient does not change significantly increasing with elliptically circular air holes radius, but reducing almost linearly with increasing wavelengths. Especially, for X-polarization, the non-linear coefficient is up to 44.3679 $W^{-1}km^{-1}$ and 28.1431 $W^{-1}km^{-1}$ for Y-polarization at 1550nm. The results of birefringence and non-linearity are compared individually with the former values that are presented in the literature [3], [16].

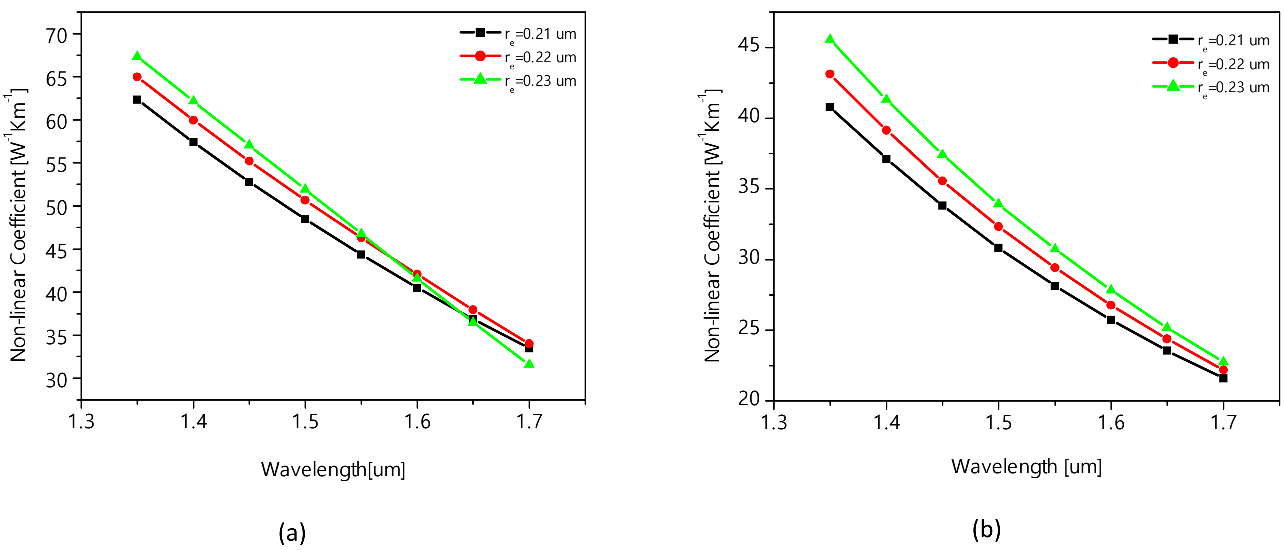


Fig. 7. Influence of r_e on non-linearity for (a) X-polarization and (b) Y-polarization

Here, it has been possible to trade off high chromatic dispersion, high birefringence and large non-linearity by using our optimized design. To reach manufacturing process, confinement and bending loss is considered. For our design, the confinement loss is found to be around 0.1926 dB/km.

Finally, a comparison is made between properties of the proposed SPCF for broadband dispersion compensation and some other PCFs designed for the same. The comparison between these fibers are presented in Table 1 which takes into account the magnitude of average negative dispersion, dispersion variation and birefringence to compensate the accumulated dispersion of the SMF. The proposed DC-PCF exhibits the higher value of the average negative dispersion with lower dispersion variation that those presented before.

Table 1. Comparison between properties of the proposed DC-PCFs and other DC-PCFs

PCFs	Average dispersion ps/(nm.km)	Band(nm) with dispersion variation	B (1550nm)
Proposed SPCF	-609.32(X) -396.33(Y)	1350-1600(14.26) 1350-1800(9.34)	0.0170
Ref. [3]	-227	1350-1675(11)	0.0170
Ref. [18]	-179	1480-1675(2.1)	-
Ref. [19]	-212	1350-1675(11)	-

4 CONCLUSION

In round up, we have put forward a silica spiral PCF with ultrahigh chromatic dispersion, birefringence and nonlinearity by employing defected elliptical core in the center of the fiber. It will be a significant design to determine above three features simultaneously by changing one parameter and using only one material that provides freedom in the proposed design. Within a wavelength range of 1350–1800 nm, the proposed PCF recommends ultrahigh chromatic dispersion of (-1037.49)/(-574.411276) ps/(nm km), high birefringence up to 0.0232 and large nonlinearity up to 67.34/45.55 $W^{-1}km^{-1}$ for X/Y-polarization. These characteristics promise to pave the way for a highly efficient and outstanding partner in wideband signal processing applications in fiber optic communication.

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