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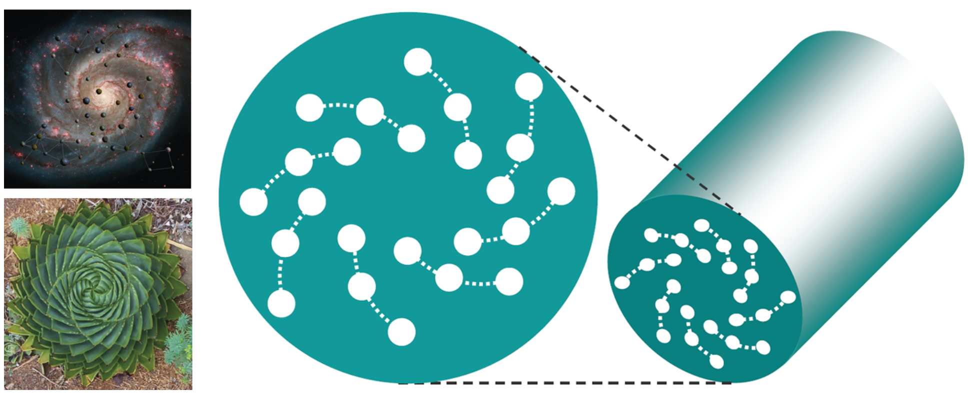
Chengcheng Gui
Jian Wang, Member, IEEE



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Elliptical–Spiral Photonic Crystal Fibers With Wideband High Birefringence, Large Nonlinearity, and Low Dispersion

Chengcheng Gui and Jian Wang, *Member, IEEE*

Wuhan National Laboratory for Optoelectronics, College of Optoelectronic Science and Engineering,
Huazhong University of Science and Technology, Wuhan 430074, China

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Corresponding author: J. Wang (e-mail: jwang@hust.edu.cn).

Abstract: We design a novel elliptical–spiral soft-glass photonic crystal fiber (PCF) achieving simultaneous wideband high birefringence, large nonlinearity, and low chromatic dispersion. Through the optimization of the arrangement and diameter of circular air holes, the designed elliptical–spiral PCF offers high birefringence up to 0.05554, large nonlinearity up to 3089/3079 $W^{-1} \cdot km^{-1}$, and low chromatic dispersion of (-95.45, 0)/(-372.6, 153.2) ps/nm/km for X/Y-polarization within a wavelength range of 1000–1800 nm.

Index Terms: Birefringence, chromatic dispersion, elliptical–spiral photonic crystal fiber, nonlinearity.

1. Introduction

Recently, photonic crystal fiber (PCF) has gained increased interest in fiber optical communications due to its unique properties [1]. Compared to conventional single-mode fiber (SMF), it provides increased freedom in the design of the microstructure of PCF, which allows for the flexible engineering of various properties including birefringence [2], nonlinearity [3], [4], and chromatic dispersion [5], [6]. For example, 1) birefringence can be produced by adopting asymmetric structures [7]–[9] in the PCF design. Many methods can realize birefringence: The fiber core can be designed to be asymmetrical (e.g., double or triple defects in the fiber core); the air holes can be elliptical instead of circular one [8], [9]. High birefringence up to the order of 10^{-2} can be obtained by using elliptical air holes, but the fabrication of elliptical-hole PCFs is a challenging problem. 2) Enhanced nonlinearity can be easily accomplished by the use of different materials and different sizes of PCF. In contrast to pure silica [10], glasses with different compositions (e.g., lead-silicate glasses and soft glasses) are suitable choices. The compound glasses also offer an added advantage of low softening temperatures. The extrusion technique has been employed to enable the fabrication of lead-silicate PCF designs with complicated structures [11]. 3) The chromatic dispersion can be tailored by changing the large index contrast of PCF and the number, shape, and arrangement of air holes [12], [13]. Controlling the chromatic dispersion of PCF is easily realized by optimizing the diameter of circular air holes and the pitch size (center-to-center distance between the air holes).

Although high birefringence, large nonlinearity, and low chromatic dispersion have been separately shown in different PCF structures, there has been little research reported in simultaneously

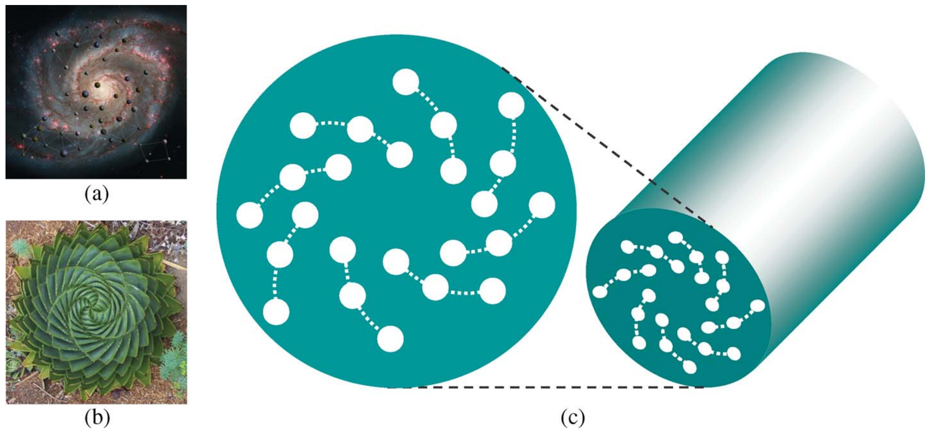


Fig. 1. (a) and (b) Spiral shape in nature and (c) the structure of an elliptical–spiral PCF.

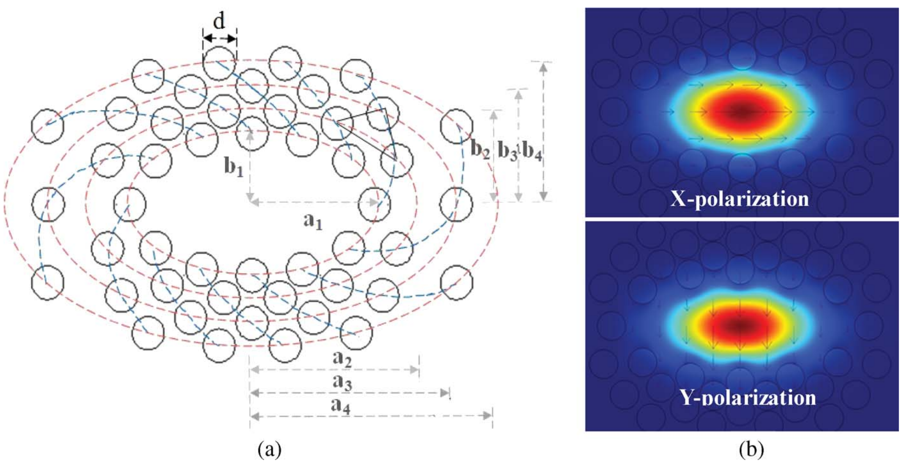


Fig. 2. Cross section of elliptical–spiral PCF and field distributions of fundamental modes for *X* and *Y* polarizations.

achieving all of these features. In this scenario, a laudable goal would be to take full use of the design freedom of PCF to obtain simultaneous wideband high birefringence, large nonlinearity, and low chromatic dispersion, which might be of importance in highly efficient wideband signal processing applications. In addition, it is also desired to decrease the complexity of PCF design; hence, circular air holes with new tailoring arrangement are preferred.

In this letter, we present a new structure of PCF with circular air holes that are tailored in an elliptical–spiral arrangement. The designed elliptical–spiral PCF exhibits simultaneous wideband high birefringence, large nonlinearity, and low chromatic dispersion.

2. Structure and Design of Elliptical–Spiral PCF

As shown in Fig. 1(a) and (b), there are various interesting spiral phenomena in nature, such as galaxies, nautilus, shells of snails, barbados aloe, distribution of sunflower seeds, etc. The designed structure of elliptical–spiral PCF, as illustrated in Fig. 1(c), comes from such spiral appearance. It has an elliptical core with several spiral arms composed of circular air holes. The cross-section view of the elliptical–spiral PCF with design details is shown in Fig. 2(a). Compared to the conventional hexagonal lattice structure, spiral lattices of circular air holes (blue dashed lines) are introduced as the cladding of the PCF. In order to produce birefringence, an elliptical–spiral PCF is considered, i.e., an elliptical core region is formed at the center instead of the circular core region that

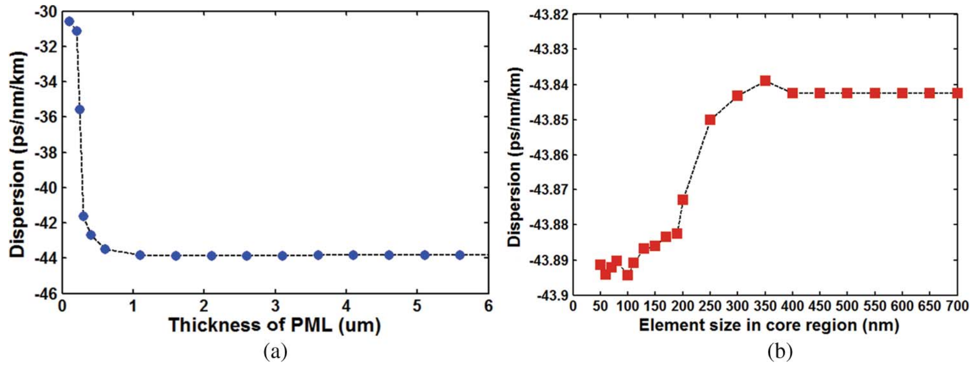


Fig. 3. Dispersion as functions of (a) thickness of PML and (b) element size in core region.

was proposed in the previous equiangular structure [10], [14]. As shown in Fig. 2(a), the elliptical–spiral PCF has 12 spiral arms, each containing four circular air holes with a diameter of d. Different spiral arms appear with variable bending and changeable spacing between circular air holes.

In order to present a quantitative design, the elliptical–spiral PCF structure can be described in an alternative angle of view: The PCF is composed of four elliptical lattices (red dashed lines), each having 12 circular air holes. Note that four elliptical lattices have the same ellipticity ratio $(a_1 : b_1 = a_2 : b_2 = a_3 : b_3 = a_4 : b_4)$ and equally increasing major length $(a_2 - a_1 = a_3 - a_2 = a_4 - a_3)$. In the innermost elliptical lattice, the arc length between the neighboring air holes is identical. The air hole in the outer elliptical lattice is placed in such a position that it constructs an isosceles triangle together with two nearby air holes in the inner elliptical lattice. The field distributions of fundamental modes for X/Y-polarization are shown in Fig. 2(b). The mode is confined well in the elliptical core region. Compared to existing structures, the elliptical–spiral PCF structure can potentially offer the following design benefits for achieving simultaneous broadband high birefringence, large nonlinearity, and low chromatic dispersion: 1) the elliptical arrangement of circular air holes provides high birefringence; 2) the spiral-shape structure is compact and able to achieve tight light confinement, small effective mode area, and large nonlinearity; 3) the increased degree of freedom enables flexible tailoring of waveguide dispersion and resultant low chromatic dispersion. Additionally, the circular air holes adopted in the elliptical–spiral PCF structure facilitate easy fabrication.

3. Results and Discussions

We calculate the field distribution and effective modal index (n_{eff}) of the designed elliptical–spiral PCF by using a full-vector finite-element method software (COMSOL). The spiral lattices of circular air holes are distributed in soft glass (SF57). The material dispersion of SF57 is taken into consideration [11]. The birefringence $(\Delta n_{\mathrm{eff}})$, nonlinearity (γ), and chromatic dispersion (D) are expressed as follows:

$$\Delta n_{\mathrm{eff}} = n_{\mathrm{eff}}^{X} - n_{\mathrm{eff}}^{Y} \tag{1}$$

$$\gamma = 2\pi n_2/(\lambda A_{\mathrm{eff}}) \tag{2}$$

$$D = -\lambda/c \cdot d^2 n_{\mathrm{eff}}/d\lambda^2 \tag{3}$$

where c is the light velocity in vacuum, λ is the wavelength, A_{eff} is the effective area of fundamental mode, and $n_2 = 4.1 \times 10^{-19}\ \mathrm{m}^2 \cdot \mathrm{w}^{-1}$ is the nonlinear refractive index of SF57 [14].

To ensure accurate calculations, we verify the convergence of the calculated chromatic dispersion values under different thickness of perfectly matched layer (PML) and different element sizes in the elliptical core region, respectively. Fig. 3(a) shows chromatic dispersion values at 1550 nm with the thickness of PML changed from 0.1 to 6 μm. It can be clearly seen that the chromatic dispersion values change fast and then vary slowly with the increase in the thickness of PML. In particular, when the thickness of PML is greater than 1 μm, the chromatic dispersion values keep almost constant.

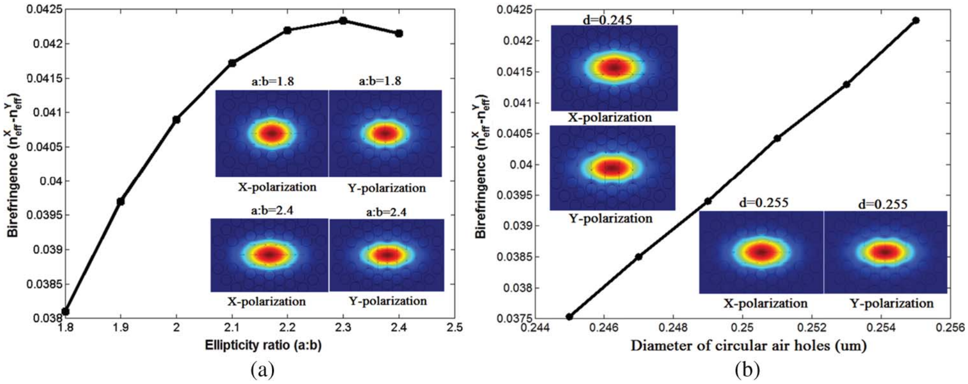


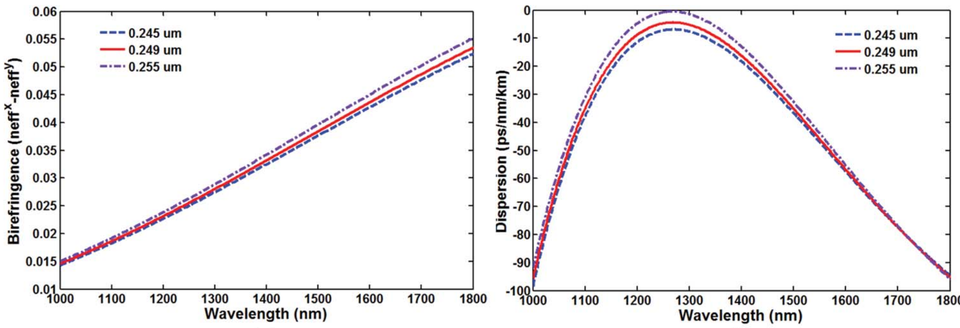
Fig. 4. Birefringence versus (a) ellipticity ratio and (b) diameter of circular air holes.

Hence, a 1-μm-thick PML is employed when calculating chromatic dispersion values. As shown in Fig. 3(b), we obtain chromatic dispersion values at 1550 nm by varying the element size from 800 to 50 nm in the core region of the elliptical–spiral PCF. When the element size in the elliptical core region is small enough, subtle changes happen in chromatic dispersion values. It is expected that an element size of 50 nm is good enough to calculate chromatic dispersion values.

In contrast to the conventional SMF, the elliptical–spiral PCF provides increased freedom in tailoring birefringence, nonlinearity, and chromatic dispersion. We first examine the dependence of birefringence on the ellipticity ratio and the diameter of circular air holes at 1550 nm. When fixing the diameter of all circular air holes at 0.255 μm, the birefringence as a function of the ellipticity ratio is shown in Fig. 4(a). The birefringence increases first and then decreases with the increase in ellipticity ratio. A maximum birefringence of 0.4233 is achieved under an optimized ellipticity ratio of 2.3. Shown in the insets in Fig. 4(a) are the field distributions of fundamental modes for X/Y-polarization under two ellipticity ratios of 1.8 and 2.4. With the ellipticity ratio fixed at 2.3, the dependence of birefringence on the diameter of all circular air holes is depicted in Fig. 4(b). One can clearly see that the birefringence increases with the increase in the diameter of all circular air holes. The relationship between the birefringence and the diameter of all circular air holes is approximately linear. Insets in Fig. 4(b) depict the field distributions of fundamental modes for X/Y-polarization under two different diameters of all circular air holes of 0.245 and 0.255 μm.

We then investigate the dependence of birefringence and chromatic dispersion on the wavelength under different diameters of innermost circular air holes. As shown in Fig. 5(a), the birefringence increases almost linearly with the wavelength. With the increase in the diameter of innermost circular air holes, it is found that birefringence also increases. Due to negligible variation of dispersion between X and Y polarizations with varied diameters of innermost circular air holes, we show in Fig. 5(b) the dispersion only for the X-polarization. The chromatic dispersion values decrease with the increase in the diameter of innermost circular air holes. Note that a zero dispersion at $\sim$1266 nm can be achieved as the diameter of innermost circular air holes is chosen to be 0.255 μm. In Figs. 4 and 5, one can expect an optimized structure of the designed elliptical–spiral PCF, which has an ellipticity radio of 2.3 and a diameter of all circular air holes of 0.255 μm. With the optimized elliptical–spiral PCF, a large birefringence of 0.04233 at 1550 nm is achieved.

We further characterize the performance of birefringence, nonlinearity, chromatic dispersion, and chromatic dispersion slope of the optimized elliptical–spiral PCF. The nonlinearity and chromatic dispersion of fundamental modes for X/Y-polarization as functions of wavelength are shown in Fig. 6. Within a wavelength range of 1000–1800 nm, the chromatic dispersion sits in ($-$95.45, 0) ps/nm/km for X-polarization and ($-$372.6, 153.2) ps/nm/km for Y-polarization, and the nonlinearity lies in (1135, 3089) $W^{-1} \cdot km^{-1}$ for X-polarization and (937, 3079) $W^{-1} \cdot km^{-1}$ for Y-polarization. Also, the chromatic dispersion for X-polarization is flatter compared to that for Y-polarization. In particular, as shown in the inset in Fig. 4, a low and flat dispersion within ($-$10, 0) ps/nm/km is achieved for X-polarization as the wavelength changes from 1170 to 1380 nm. Fig. 7 shows the



(a) (b)

Fig. 5. (a) Birefringence and (b) dispersion versus wavelength under different diameters of innermost circular air holes.

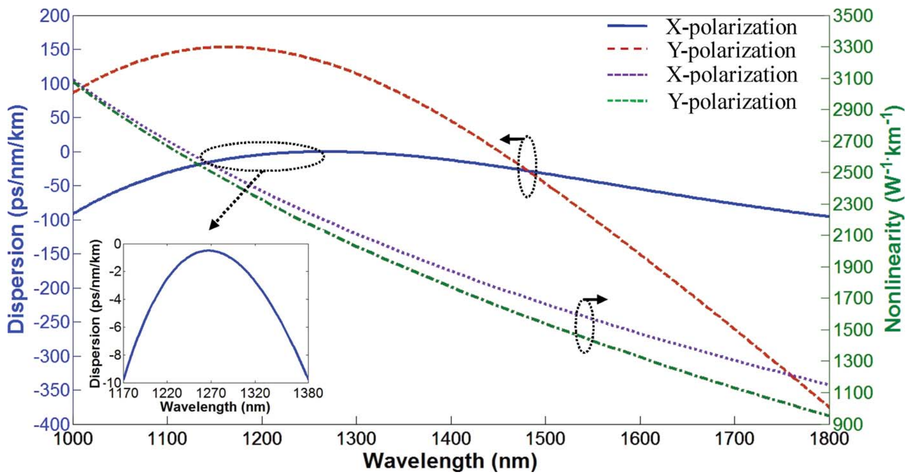


Fig. 6. Dispersion and nonlinearity versus wavelength. (Inset) Dispersion for X-polarization within 1170 and 1380 nm.

wavelength-dependent birefringence and dispersion slope for X/Y-polarization. An approximate linear relationship between the birefringence and wavelength is achieved. A maximum birefringence of 0.05554 is obtained at a wavelength of 1800 nm. The chromatic dispersion slope is evaluated to be within $(-1.669, 0.003415)$ ps/nm^2/km for X-polarization and $(-2.345, 1.754)$ ps/nm^2/km for Y-polarization as the wavelength is changed from 1000 to 1800 nm. It is expected from Figs. 3 –7 that elliptical–spiral PCF can provide simultaneous wideband high birefringence, large nonlinearity, and low chromatic dispersion.

The proposed structure employs elliptical–spiral arranged circular air holes. In comparison to conventional PCF structures supporting separate properties, the compact elliptical–spiral structure can achieve simultaneous broadband high birefringence, large nonlinearity, and low chromatic dispersion: 1) high birefringence is offered by the elliptical arrangement of circular air holes; 2) large nonlinearity is provided by the spiral-shape structure, which is compact and capable of achieving tight light confinement with small effective mode area; 3) low chromatic dispersion is enabled by tailoring the waveguide dispersion; 4) easy fabrication is feasible due to the circular air holes adopted in the structure. In particular, one distinct feature of the designed elliptical–spiral PCF is the increased freedom to tailor the birefringence, nonlinearity, and chromatic dispersion, such as ellipticity ratio, diameter of circular air holes, pitch size of circular air holes, number of spiral arms, and number of circular air holes in each spiral arm. With future improvement, comprehensive optimization of all of these parameters, together with the proper choice of different materials (e.g., tellurite,

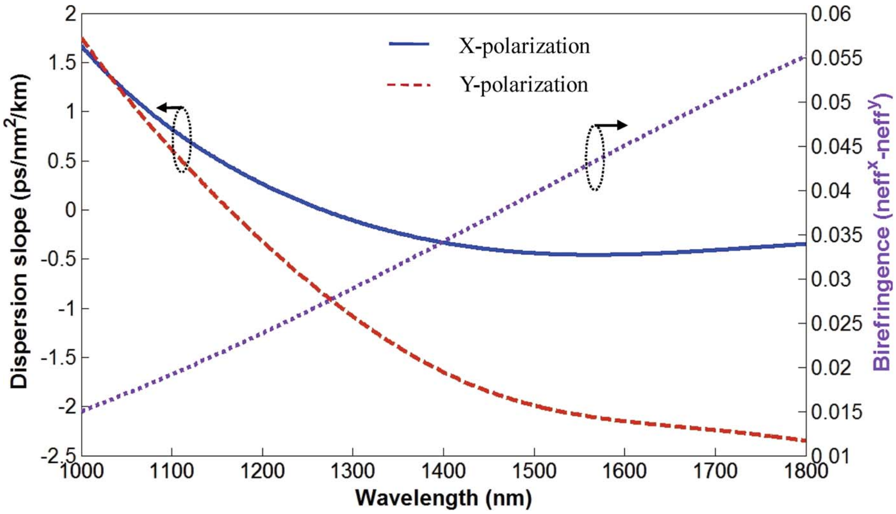


Fig. 7. Dispersion slope and birefringence versus wavelength.

polymers, compound silica glasses, Bi_2O_3 glass, and chalcogenide classes) would be desired to achieve superior performance.

4. Conclusion

In summary, we have presented a novel design of elliptical–spiral soft-glass PCF. A full-vector finite-element method is used to characterize the performance of the designed elliptical–spiral PCF. By optimizing the ellipticity ratio and the diameter of circular air holes, we obtain simultaneous wideband high birefringence, large nonlinearity, and low chromatic dispersion. Within a wavelength range of 1000–1800 nm, the designed PCF offers high birefringence up to 0.05554, large nonlinearity up to 3089/3079 $W^{-1} \cdot km^{-1}$, and low chromatic dispersion of ($-$95.45, 0)/($-$372.6, 153.2) ps/nm/km for X/Y-polarization. The dispersion slope lies in $(-1.669, 0.003415)$ ps/nm^2/km for X-polarization and $(-2.345, 1.754)$ ps/nm^2/km for Y-polarization.

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