Optica Applicata, Vol. XLV, No. 1, 2015
DOI: 10.5277/oa150102

Soft glass spiral photonic crystal fiber for large nonlinearity and high birefringence

S. REVATHI*, SRINIVASA INABATHINI, RAM SANDEEP

School of Electronics and Communication, VIT University, Vellore, Tamil Nadu, India

*Corresponding author: srevathi@vit.ac.in

This paper presents a soft glass spiral photonic crystal fiber with circular air holes for achieving high birefringence, large nonlinearity and large negative dispersion. The material used here for designing the fiber is soft glass (SF-57). A central defect air hole is being introduced in the core for achieving high birefringence and for different ellipticity ratios the effect of various optical properties of a photonic crystal fiber are studied. The structure proposed has a high birefringence in the order of 10^{-2}, high nonlinearity of 5828 $W^{-1}km^{-1}$ and high negative dispersion of –1546.6 ps/nm·km at 0.850 μm. A numerical approach based on the finite element method is used for the design and simulation of the structure. Due to the optimization in the cladding air holes, the fiber can be used as polarization maintaining fibers, in dispersion compensation and other nonlinear applications.

Keywords: birefringence, dispersion, finite element method (FEM), spiral photonic crystal fiber (SPCF).

1. Introduction

Traditional optical fibers which are used in telecommunication applications have a solid core surrounded by a solid cladding of lower refractive index compared to the core, which helps for the wave guiding mechanism [1]. Photonic crystal fibers have a microscopic array of air channels running down the fiber length that provide design flexibility in tuning dispersion slope and nonlinearity. A photonic crystal fiber (PCF) normally consists of a solid core and the cladding consists of a solid matrix material with almost same refractive index as a core with some air holes disposed into it [2]. The cladding air holes help to lower the refractive index of the cladding which allows the optical wave guidance. Based on the operation, light is guided by two ways either through total internal reflection or through a photonic band gap [3, 4]. In some fibers light is guided by a photonic band gap which is created by the microstructured air holes. So, these types of fibers can propagate light even with a lower core index [5].

PCF are more special than the conventional optical fiber in which we can alter the different optical properties of the fiber such as birefringence, dispersion, effective mode area, *etc*. Apart from the most used and primary hexagonal structure, there are many other structural arrangements which can be used for important applications. A spiral photonic crystal fiber (SPCF) is one of them. An equiangular spiral has been designed with negative flattened dispersion profile and high birefringence has been reported [6]. The main advantage of using a spiral PCF is due to its compactness which gives us small core area which in turn results in large nonlinearity. An equiangular spiral with soft glass background has been designed with large nonlinearity [7]. Similarly, a spiral silica fiber of high nonlinearity has been obtained by tailoring the design parameters [8]. A highly birefringent polarization maintaining fiber has been designed by introducing a defect in the core region, which gives additional flexibility for tailoring dispersion [9]. High birefringence and nonlinearity are obtained by removing the identical air holes in x- and y-direction as to make the design asymmetrical [10].

In this paper, dispersion profile [11], birefringence and nonlinearity are investigated by introducing some defect in the core region with an elliptical air hole. High birefringence in terms of 10^{-2} and large nonlinearity have been obtained. In addition to that, high negative dispersion is achieved for certain wavelength region. So, these types of photonic crystal fibers can be used for different nonlinear applications like super continuum generation [12] and second harmonic generation [13].

2. Properties of photonic crystal fiber

Various properties of PCF like birefringence, dispersion, effective mode area and nonlinearity are discussed. The maintenance of the input polarization state is described in terms of a phenomenon called fiber birefringence. It is a property of the fiber which depends on the direction of propagation and polarization of the transmitted light. It is defined as the difference between the effective index of the x-polarized and the y-polarized component of the light.

$$B = \mathrm{Re}(n_{\mathrm{eff}}^{x}) - \mathrm{Re}(n_{\mathrm{eff}}^{y}) \tag{1}$$

where n_{eff}^{x} and n_{eff}^{y} are the effective refractive indexes of the two fundamental orthogonally polarized modes.

Birefringence is a desirable property in fiber optics. In many sensing applications where light has to maintain a linear polarization state, often high birefringence is required [14, 15]. The key point in realizing the birefringence is to break the symmetry of structure and increase the effective index difference between the two orthogonal polarization modes [16]. The structural symmetry can be destroyed either by varying the air holes radius near the core or by changing the shape of the air hole to elliptical or by introducing a defect air hole at the center of the core. Birefringence in the order of 10^{-2} can be achieved in photonic crystal fibers.

Dispersion causes pulse broadening of transmitted pulses along the fiber. Chromatic dispersion contains both material and waveguide dispersion. The chromatic dispersion can be calculated by the following equation:

$$D = -\frac{\lambda}{c}\frac{\mathrm{d}^2 n_{\mathrm{eff}}}{\mathrm{d}\lambda^2} \quad [\mathrm{ps/nm\cdot km}] \tag{2}$$

where c is the velocity of light and λ is the operating wavelength. The corresponding effective refractive index of the operating wavelength for material dispersion is given by the Sellmeier equation

$$n^2(\omega) = 1 + \sum_{j=1}^{M} \frac{B_j \omega_j^2}{\omega_j^2 - \omega^2} \tag{3}$$

where ω_j is the resonance frequency and B_j is the resonance strength. Chromatic dispersion [17] can be altered in many ways which include varying the radius of the air holes near the core, varying the number of air holes, and the shape of the air holes in the cladding region. So by tailoring these design parameters, we can obtain large negative dispersion [18] which can be used in dispersion compensation [19, 20]. The waveguide contribution helps to manage the dispersion. Such fibers with good waveguide contribution can be used in dispersion management which can be attained by varying the air hole filling factor.

Effective mode area A_{eff} is the area occupied by the fundamental mode. The intensity will be maximum at the fiber core,

$$A_{\mathrm{eff}} = \frac{\left[\iint |E(x, y)\mathrm{d}x\mathrm{d}y|^2\right]^2}{\iint |E(x, y)\mathrm{d}x\mathrm{d}y|^4} \quad [\mu\mathrm{m}^2] \tag{4}$$

Effective area increases with an increase in wavelength and this helps in finding nonlinearity. Effective mode area depends on fiber parameters like core diameter, refractive index difference between the core and the cladding, and air hole filling factor.

The nonlinearity parameter of the photonic crystal fiber is given by

$$\gamma = \frac{n_2 \omega}{c A_{\mathrm{eff}}} = \frac{2\pi n_2}{\lambda A_{\mathrm{eff}}} \quad [\mathrm{W^{-1}m^{-1}}] \tag{5}$$

where n_2 is the nonlinear refractive index coefficient (4.1×10^{-19} $\mathrm{m^2/W}$ for SF-57), c is the velocity of light, and λ is the operating wavelength. Nonlinearity can be increased using different materials. High nonlinearity comes into consideration when the effective mode area of the fiber is very low and the nonlinear refractive index coefficient is large. So nonlinearity is inversely proportional to the effective mode area.

3. Structure of proposed spiral PCF

The structure is designed using the tool Comsol 3.5. It is based on FEM (finite element method), an accurate numerical method used to find solution to boundary problems. The proposed structure with circular air holes has been shown in Fig. 1. The structure has a spiral lattice of circular air holes, which consists of eight spiral arms and five circular air holes or rings in each spiral arm and an elliptical air hole in the center with the semi-major axis *a* and semi-minor axis *b*.

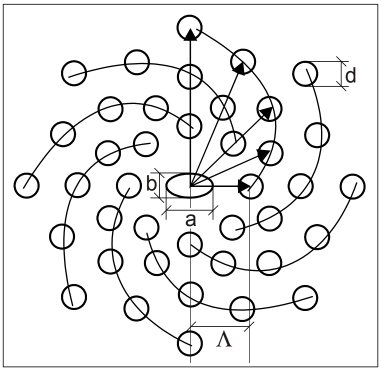

Fig. 1. Structure of a circular spiral PCF with an elliptical defect air hole, *d* – diameter of air hole, *Λ* – pitch.

The angle between two rings in a spiral arm can be arranged by 180/*N* degrees, where *N* is the number of spiral arms in the structure. Here *N* should be selected such that there should be no overlapping of the air holes. So the maximum value of *N* depends on the core diameter and the diameter of the air hole. The distance between the two adjacent air holes of each spiral arm varies in geometric progression. The core diameter is 1.05 μm. The diameter of the air hole is 0.21 μm which is constant throughout

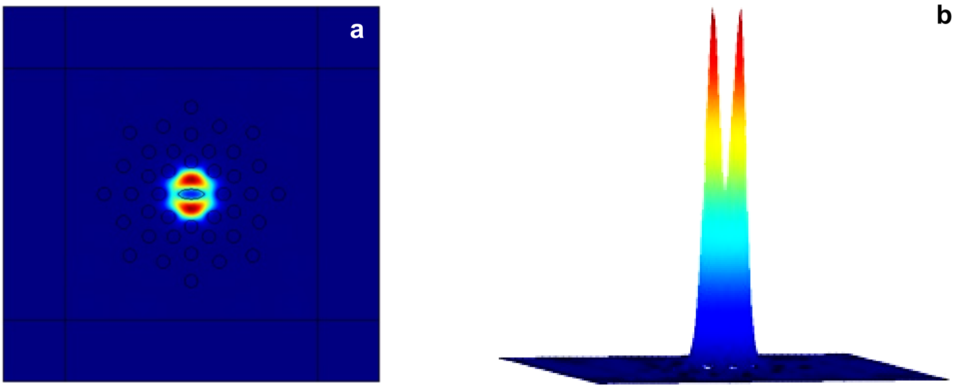

Fig. 2. Simulated structure showing light confinement: two-dimensional (**a**) and three-dimensional (**b**) plot.

the structure. A perfectly matched layer (PML) is created around the structure for perfect absorption of the waves. PML layer width which we used here is 1 μm.We tailor the semi-major axis and semi-minor axis of the elliptical defect air hole to obtain ellipticities of 2, 2.5, 3, 3.5 for soft glass (SF-57).The main advantage of using this spiral lattice is that the number of air holes we use here gets reduced by a large number when compared to the normal triangular lattice structure which leads to a small core area. Because of this small core area, the effective mode area will be less. The semi-major axis *a* we used here is 0.2 μm and by varying the semi-minor axis *b*, the ellipticity ratios of 2, 2.5, 3, and 3.5 have been obtained. The proposed method can be employed using the drop perpendicular method or the stack and draw method [21].

We calculate the effective mode index and the effective area of the circular spiral photonic crystal fiber using the finite element method in Comsol 3.5.

Figure 2 shows the light confinement at 1.55 μm for soft glass (SF-57) in both two- and three-dimensional pattern.

4. Results and discussion

The wavelength is varied widely from 0.65 μm to 1.95 μm during the analysis. The $N_{\rm eff}$ value is obtained by simulating the structure. The variation in the effective refractive index with wavelength is shown in Fig. 3. We can see in the figure that the effective refractive index decreases linearly with an increase in wavelength. We also observe that as we increase the ellipticity of the air hole, the effective index increases.

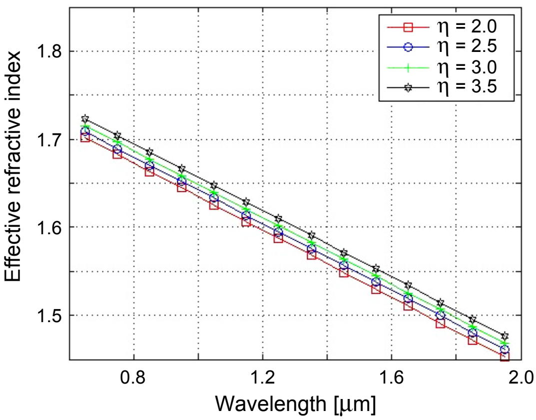

Fig. 3. Effective refractive index *versus* wavelength for different ellipticity ratios of 2, 2.5, 3, 3.5.

Variation in birefringence with wavelength is shown in Fig. 4. The birefringence in the order of 10^{-2} is achieved by altering the design parameters in the structure.

Birefringence of a fiber increases linearly with wavelength. High birefringence of 2.96×10^{-2} is obtained at 1.55 μm wavelength for the ellipticity ratio of 3.5. It is comparatively higher than the birefringence reported [6].

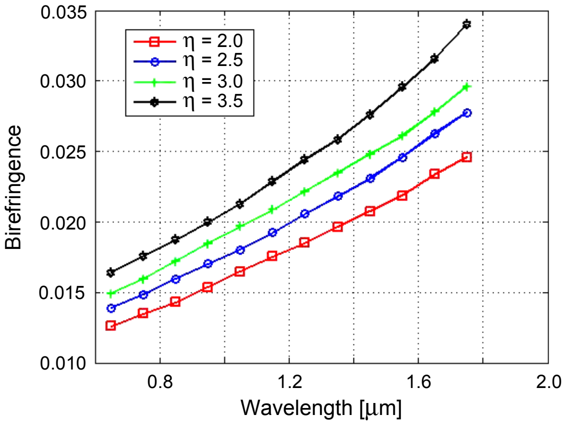

Fig. 4. Birefringence *versus* wavelength for different ellipticity ratios of 2, 2.5, 3, 3.5.

Chromatic dispersion is the variation in group velocity with a variation in wavelength. Dispersion in PCF is highly effected by the size and positioning of the air holes and the pattern in which the air holes are arranged. Other important design parameters which can tailor the dispersion are the core radius and number of spiral arms. Figure 5 shows the variation in dispersion with wavelength for different ellipticity ratios. It is observed that for the ellipticity ratio of 2, at 0.850 μm we have obtained high negative dispersion of –1546.6 ps/nm·km, while at 1.05 μm negative dispersion of –493.3 ps/nm·km is obtained. Two zero dispersions have been observed for the ellipticity ratio of 2 at 1.14 μm and 1.90 μm, respectively.

For the ellipticity ratio of 2.5, we have one zero dispersion at 1.156 μm, for the ellipticity ratio of 3 we have one zero dispersion at 1.18 μm and for the ellipticity ratio of 3.5 also we have one zero dispersion at 1.20 μm. The negative dispersion region can be used for dispersion compensation due to its high negative dispersion value

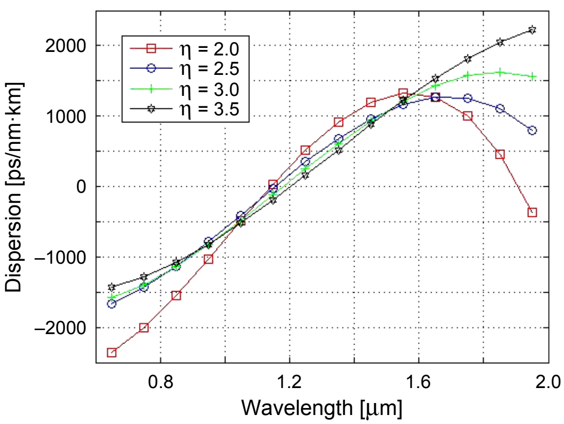

Fig. 5. Dispersion *versus* wavelength for different ellipticity ratios of 2, 2.5, 3, 3.5.

which is not possible with conventional optical fibers. Due to the low dispersion coefficient, the length of the dispersion compensating fiber (DCF) will be very large. So, this is an advantage in PCFs when compared to conventional optical fibers because of the large negative dispersion value and reduction in length of DCF.

In Figure 6**a**, we examined the effect of an ellipticity ratio on the effective area and nonlinearity. Effective area increases linearly with wavelength. The effective area of a spiral PCF will be considerably smaller and this results in high nonlinearity [22] at large wavelengths which can be used for super continuum generation (SCG) pump lasers [23, 24]. This less effective area issue is an advantage of the photonic crystal fiber over a conventional optical fiber. The effective area in PCF is much smaller when compared to the normal optical fiber.

In Figure 6**b**, the structure shows very high nonlinearity because of a small effective area. For the ellipticity ratio of 2, it is observed that the high nonlinearity of

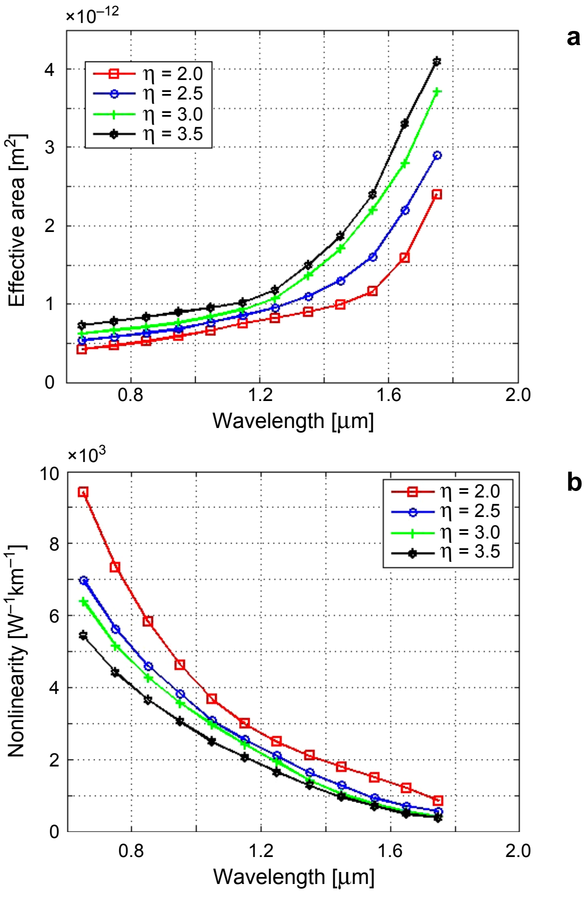

Fig. 6. Effective area (**a**), and nonlinearity (**b**) *versus* wavelength for different ellipticity ratios of 2, 2.5, 3, and 3.5.

1598 $W^{-1}km^{-1}$ at 1.55 μm has been observed which decreases accordingly to the other ellipticity ratios. The nonlinearity which we have obtained is high compared in [6]. Another reason for the high nonlinearity is the large value of the nonlinear refractive index coefficient n_2 (4.1×10^{-19} m^2/W for SF-57) of soft glass [25]. So when n_2 is high and the effective area is small, it becomes a favorable condition for high nonlinearity. The effective area which we have calculated for the proposed design increases with wavelength in the order of 10^{-13} and at higher wavelengths it is of order of 10^{-12}. The nonlinearity of the proposed structure decreases with wavelength because the amount of light confined at the center of the core is less at higher wavelengths. The light confined spreads away from the core which results in the increase in the effective mode area [26]. When the light confinement is high at the center of the core, the effective mode area will be small, otherwise the higher the light confinement is, the lower is the effective area and the higher is the nonlinearity.

5. Conclusion

A circular spiral photonic crystal fiber has been designed in which circular air holes are arranged in a spiral lattice. The structure is designed for different ellipticity ratios of the center defect air hole and the effect of this on various fiber properties is analyzed. Numerical results state that by introducing some defect in the core region, the birefringence of the order 10^{-2} can be achieved, which is very high compared to conventional fibers. These fibers can be used as polarization maintaining fibers which have more control over polarization. High birefringence of 2.96×10^{-2} has been observed at 1.55 μm for the ellipticity ratio of 3.5 and high nonlinearity of 5828 $W^{-1}km^{-1}$ and high negative dispersion of –1546.6 ps/nm-km at 0.850 μm for the ellipticity ratio of 2. The designed structure has negative dispersion for certain wavelength region and hence can be used for dispersion compensation fibers. The structure with the ellipticity ratio of 2 has high birefringence, dispersion and nonlinearity. Hence this is an optimized design and due to the large nonlinearity, the fiber has its prominence in nonlinear device applications.

References

[1] RUSSELL P.S.J., *Photonic-crystal fibers*, Journal of Lightwave Technology **24**(12), 2006.

[2] WEST J.A., *Photonic Crystal Fibers*, Laser and Electro Optics Society, IEEE, 1, 2001, pp. 14–15.

[3] LAEGSGAARD J., HANSEN K.P., NIELSEN M.D., HANSEN T.P., RIISHEDE J., HOUGAARD K., SORENSEN T., LARSEN T.T., MORTENSEN N.A., BROENG J., JENSEN J.B., BJARKLEV A., *Photonic crystal fibers*, Proceedings of the 2003 SBMO/IEEE MTT-S International Microwave and Optoelectronics Conference IMOC 2003, Vol. 1, 2003, pp. 259–264.

[4] KNIGHT J.C., BIRKS T.A., RUSSELL P.S.J., ATKIN D.M., *All-silica single-mode optical fiber with photonic crystal cladding*, Optics Letters **21**(19), 1996, pp. 1547–1549.

[5] WEST J.A., VENKATARAMAM N., SMITH C.M., GALLAGHER M.T., *Photonic crystal fibers*, 27th European Conference on Optical Communication, ECOC '01, Vol. 4, 2001, pp. 582–585.

[6] Islam M.A., Alam M.S., *Design optimization of equiangular spiral photonic crystal fiber for large negative flat dispersion and high birefringence*, Journal of Lightwave Technology **30**(22), 2012, pp. 3545–3551.

[7] Agrawal A., Kejalakshmy N., Rahman B.M.A., Grattan K.T.V., *Soft glass equiangular spiral photonic crystal fiber for supercontinuum generation*, IEEE Photonics Technology Letters **21**(22), 2009, pp. 1722–1724.

[8] Muhammad Nazmul Hossain, M. Shah Alam, Dihan Md. Nuruddin Hasan, K.M. Mohsin, *A highly nonlinear spiral photonic crystal fiber for Tailoring two zero dispersion wavelengths in the visible region*, Photonics Letters of Poland **2**(3), 2010, pp. 143–145.

[9] Islam M.A., Alam M.S., *Design of a polarization-maintaining equiangular spiral photonic crystal fiber for residual dispersion compensation over E+S+C+L+U wavelength band*, IEEE Photonics Technology Letters **24**(11), 2012, pp. 930–932.

[10] Samiul Habib M., Selim Habib M., Imran Hasan M., Razzak S.M.A., *Highly nonlinear polarization maintaining two zero dispersion spiral photonic crystal fiber using artificial defects*, Optical Fiber Technology **19**(6), 2013, pp. 539–542.

[11] Franco M.A.R., Serrao V.A., Sircilli F., *Microstructured optical fiber for residual dispersion compensation over S+C+L+U wavelength bands*, IEEE Photonics Technology Letters **20**(9), 2008, pp. 751–753.

[12] Dudley J.M., Genty G., Coen S., *Supercontinuum generation in photonic crystal fiber*, Reviews of Modern Physics **78**(4), 2006, pp. 1135–1184.

[13] Wijeratne I.N.M., Kejalakshmy N., Agrawal A., Rahman B.M.A., Grattan K.T.V., *Numerical analysis of second harmonic generation in soft glass equiangular spiral photonic crystal fibers*, IEEE Photonics Journal **4**(2), 2012, pp. 357–368.

[14] Peng Song, Yanrong Tong, Xinlian Chen, *A novel high birefringence photonic crystal fiber with squeezed elliptical holes*, 2010 3rd International Conference on Biomedical Engineering and Informatics (BMEI), Vol. 7, 2010, pp. 3024–3027.

[15] Ju J., Jin W., Demokan M.S., *Properties of a highly birefringent photonic crystal fiber*, IEEE Photonics Technology Letters **15**(10), 2003, pp. 1375–1377.

[16] Samiul Habib M., Selim Habib M., Razzak S.M.A., Goffar Khan M.A., Namihira Y., Hossain M.A., *Design of highly birefringent holey fibers with near-zero ultra-flattened chromatic dispersion and ultralow confinement loss*, Journal of Microwaves, Optoelectronics and Electromagnetic Applications **12**(1), 2013, pp. 102–110.

[17] Ademgil H., Haxha S., *Highly birefringent photonic crystal fibers with ultralow chromatic dispersion and low confinement losses*, Journal of Lightwave Technology **26**(4), 2008, pp. 441–448.

[18] So Eun Kim, Bok Hyeon Kim, Chung Ghiu Lee, Sejin Lee, Kyunghwan Oh, Chul-Sik Kee, *Elliptical defected core photonic crystal fiber with high birefringence and negative flattened dispersion*, Optics Express **20**(2), 2012, pp. 1385–1391.

[19] Jianhua Li, Rong Wang, Jingyuan Wang, Zhiyong Xu, Yang Su, *Novel large negative dispersion photonic crystal fiber for dispersion compensation*, 2011 Second International Conference on Mechanic Automation and Control Engineering (MACE), 2011, pp. 1443–1446.

[20] Tee D.C., Abu Bakar M.H., Tamchek N., Mahamd Adikan F.R., *Photonic crystal fiber in photonic crystal fiber for residual dispersion compensation over E+S+C+L+U wavelength band*, IEEE Photonics Journal **5**(3), 2013, article 7200607.

[21] Agrawal A., Azabi Y.O., Rahman B.M.A., *Stacking the equiangular spiral*, IEEE Photonics Technology Letters **25**(3), 2013, pp. 291–294.

[22] Chengcheng Gui, Jian Wang, *Elliptical–spiral photonic crystal fibers with wideband high birefringence, large nonlinearity, and low dispersion*, IEEE Photonics Journal **4**(6), 2012, pp. 2152–2158.

[23] Kudlinski A., Bouwmans G., Douay M., Taki M., Mussot A., *Dispersion-engineered photonic crystal fibers for CW-pumped supercontinuum sources*, Journal of Lightwave Technology **27**(11), 2009, pp. 1556–1564.

[24] LEONG J.Y.Y., PETROPOULOS P., PRICE J.H.V., EBENDORFF-HEIDEPRIEM H., ASIMAKIS S., MOORE R.C., FRAMPTON K.E., FINAZZI V., FENG X., MONRO T.M., RICHARDSON D.J., *High-nonlinearity dispersion--shifted lead-silicate holey fibers fo efficient 1-μm pumped supercontinuum generation*, Journal of Lightwave Technology **24**(1), 2006, pp. 183–190.
[25] AGRAWAL A., KEJALAKSHMY N., RAHMAN B.M.A., GRATTAN K.T.V., *Soft glass spiral PCF with flat anomalous dispersion at 1064 nm and* $\gamma \gg 2000\ W^{-1}km^{-1}$ *at 1550 nm*, Conference on Optical Fiber Communication – incudes post deadline papers, OFC 2009, pp. 1–3.
[26] AGRAWAL G.P., *Nonlinear Fiber Optics*, Academic, New York, 1995.

Received April 3, 2014
in revised form December 5, 2014