Designing of a polarization beam splitter for the wavelength of 1310 nm on dual-core photonic crystal fiber with high birefringence and double-zero dispersion*

Bao Ya-Jie(鲍亚杰), Li Shu-Guang(李曙光)†, Zhang Wan(张 婉), An Guo-Wen(安国文), and Fan Zhen-Kai(范振凯)

Key Laboratory of Metastable Materials Science and Technology, College of Science, Yanshan University, Qinhuangdao 066004, *China*

(Received 16 January 2014; revised manuscript received 18 March 2013; published online 10 August 2014)

We have proposed a novel kind of photonic crystal fiber which contains two asymmetric cores. The birefringence and the dispersion are numerically analyzed based on finite element method when the size of the air holes and the pitch of two adjacent air holes are changed. It is shown that the proposed photonic crystal fiber has high birefringence up to the order of 10^{-2} and double-zero dispersion points are at the wavelengths of 1310 nm and 800 nm, simultaneously. At the same time, the normalized power and the extinction ratios of the proposed photonic crystal fiber have been simulated. It is demonstrated that, at the wavelength of 1310 nm, the *x*-polarized mode and the *y*-polarized mode are separated when the propagation distance is 2.481 mm.

Keywords: photonic crystal fiber, birefringence, zero dispersion, polarization beam splitter

PACS: 42.81.–i, 42.25.Lc, 11.55.Fv, 42.81.Pa **DOI:** 10.1088/1674-1056/23/10/104218

1. Introduction

Since the invention of the first photonic crystal fiber (PCF) in 1996,[1] PCFs have attracted great attention of the researchers because of their excellent performance. Compared to the conventional optical fiber, PCF has many unique properties such as high birefringence,[2–4] adjustable dispersion,[5–8] single-mode transmission,[9,10] high nonlinear,[11,12] a maximum or minimum effective mode field area,[13,14] and so on.

The PCFs with high birefringence and zero dispersion have wide applications in the field of communication and sensing systems. In 1980s, the invention of polarization maintaining fiber (PMF) made the birefringent properties of fibers become a hot research topic. Between 2000 and 2001, researchers in University of Bath cooperated with the researchers coming from Denmark Crystal Fiber Company and the Danish Institute of Technology to study PCFs with high birefringence in different structures[15,16] as well as the researchers of the NNT Company of Japan.[17] Since then, some new structures have been also proposed.[18–21] Huimei He *et al.* designed a high birefringence PCF with mixed air holes structures of which the birefringence is 8.247×10^{-3} at the wavelength of 1550 nm.[22] Dispersion is one of the most important parameters in PCFs and the PCFs with two zero dispersion wavelengths have important applications in the optimization of the supercontinuum and the inhibition of self-frequency shift of the soliton.[23] At present, the PCFs with characteristics of high birefringence, low-loss, zero dispersion or negative dispersion which are achieved by adjusting the structure parameters of the PCFs have already been reported.[24–27] However, in some of these researches, confinement loss is too high and some of the research is limited in the negative dispersion band. Thus, a high birefringence PCF which has the characteristics of zero dispersion at the same time will play an important role in polarization-maintaining transmission systems.

In this paper, a novel kind of photonic crystal fiber which contains two asymmetric cores has been proposed. Simulation results show that the PCF has the characteristics of high birefringence and double-zero dispersion. Finally, the transmission characteristics of this PCF, such as normalized power and extinction ratios, are simulated.

2. Design and numerical method

The cross section of the proposed PCF is illustrated in Fig. 1. The air holes are arranged in hexagons and the substrate material is quartz. In the middle of the cross section, some air holes have been removed in the horizontal direction to form the cores of the PCF. The diameter of the outer air holes (the small white circles in Fig. 1) is $d_1 = 0.45$ μm, the diameter of the air holes between two cores (the second smallest white circles in Fig. 1) is $d_2 = 0.64$ μm, the diameter of the air holes on both the upper and lower sides of the cores (the gray circles in Fig. 1) is d_x, the diameter of the air holes on the left and right sides of the cores (the black circles in Fig. 1) is d_y, the pitch of two adjacent air holes is Λ.

*Project supported by the National Natural Science Foundation of China (Grant No. 61178026) and the Natural Science Foundation of Hebei Province, China (Grant No. E2012203035).

†Corresponding author. E-mail: shuguangli@ysu.edu.cn

© 2014 Chinese Physical Society and IOP Publishing Ltd

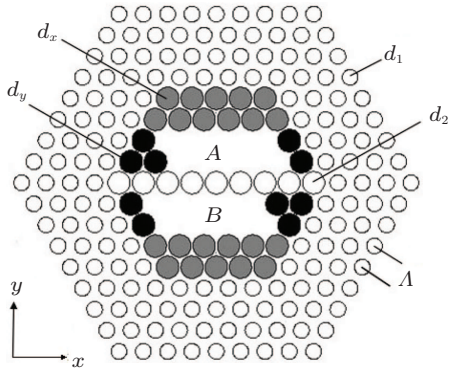


Fig. 1. The cross section of the dual-core PCF.

The mode birefringence of the PCFs can be expressed as:

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

where $\mathrm{Re}(n_{\mathrm{eff}}^{x})$ and $\mathrm{Re}(n_{\mathrm{eff}}^{y})$ are the real part of the effective refractive indexes in x-polarized and y-polarized modes respectively.

The dispersion of the PCFs $D(\lambda)$ contains two parts which are the material dispersion $D_m(\lambda)$ and the waveguide dispersion $D_\omega(\lambda)$. It can be expressed as:

$$D(\lambda) = D_m(\lambda) + D_\omega(\lambda). \tag{2}$$

The material dispersion is generally determined only by the dielectric material. It is caused by the change with wavelength of the linear refractive index of the material. It can ben expressed as:

$$D_m(\lambda) = -\frac{\lambda}{c}\frac{\partial^2 n_1(\lambda)}{\partial \lambda^2}. \tag{3}$$

However, the waveguide dispersion depends largely on the design parameters of the PCFs. It corresponds to the change of the effective refractive index of the fundamental mode with the wavelength. It can be expressed as:

$$D_\omega(\lambda) = -\frac{\lambda}{c}\frac{\partial^2 |\mathrm{Re}(n_{\mathrm{eff}})|}{\partial \lambda^2}. \tag{4}$$

The material dispersion of the PCF proposed in this paper has already been considered.

In dual-core PCFs, the general pattern can be seen as the superposition of four modes. So the normalized power at a particular wavelength can be expressed as:

$$P_{\mathrm{out}}^{x,y} = P_{\mathrm{in}}^{x,y} \cos^2\left(\frac{\pi \cdot Z}{2 \cdot L}\right), \tag{5}$$

where L is the transmission distance, and Z is the coupling length of the PCF at this particular wavelength. Thus, the extinction ratios can be explicitly derived by using the following relation:

$$ER = 10 \lg \frac{P_{\mathrm{out}}^{x}}{P_{\mathrm{out}}^{y}}. \tag{6}$$

3. Simulation and results analysis

In this paper, the dispersion and the birefringence of the proposed PCF are adjusted by changing the diameters of the air holes around the cores and the pitch of two adjacent air holes. Here, the dispersion is represented by x-polarized even mode, the birefringence is represented by the odd mode, because that the changes of the four modes of dispersion and the two modes of birefringence in the dual-core PCF are almost the same. The distributions of the four mode fields at the wavelength of $\lambda = 1310$ nm are shown in Fig. 2.

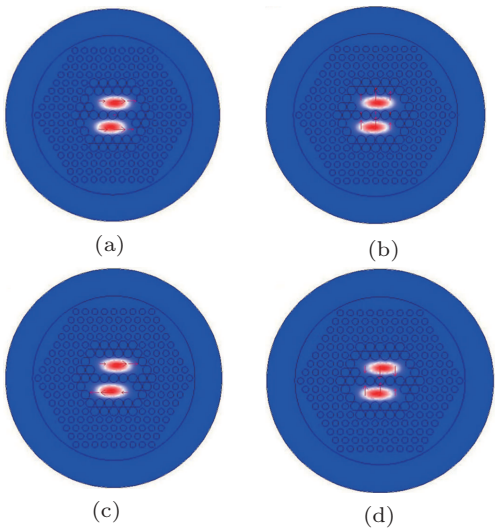


Fig. 2. (color online) Power flow distributions of the four modes in this PCF at the wavelength of $\lambda = 1310$ nm: (a) the x-polarized even mode, (b) the y-polarized even mode, (c) the x-polarized odd mode, and (d) the x-polarized odd mode.

The changes of the dispersion and the birefringence with the diameter of the air holes on both the upper and lower sides of the cores are shown in Fig. 3 when $d_y = 0.64$ μm and $\Lambda = 0.7$ μm. From Fig. 3(a) we can find that, with the increasing of d_x, the separation distance between the two zero dispersion points in the dispersion curve increases and the maximum of $D(\lambda)$ increases, too. The zero dispersion points are at the wavelengths of $\lambda = 800$ nm and $\lambda = 1310$ nm when d_x is 0.64 μm. From Fig. 3(b) we can know that the birefringence increases heavily when d_x increases. The birefringences are 1.061×10^{-2} and 1.543×10^{-2} at the wavelengths of $\lambda = 1310$ nm and $\lambda = 1550$ nm respectively.

Figure 4 shows the changes of the dispersion and the birefringence with the diameter of the air holes on the left and right sides of the cores when $d_x = 0.64$ μm and $\Lambda = 0.7$ μm. From Fig. 4(a) we can know that, when d_y increases, the dispersion curve moves upward and the separation distance between the two zero dispersion points in the dispersion curve increases. Similarly, the zero dispersion points are at the wavelengths of $\lambda = 800$ nm and $\lambda = 1310$ nm when d_y is 0.64 μm. From Fig. 4(b) we can find that the birefringence is almost unchanged.

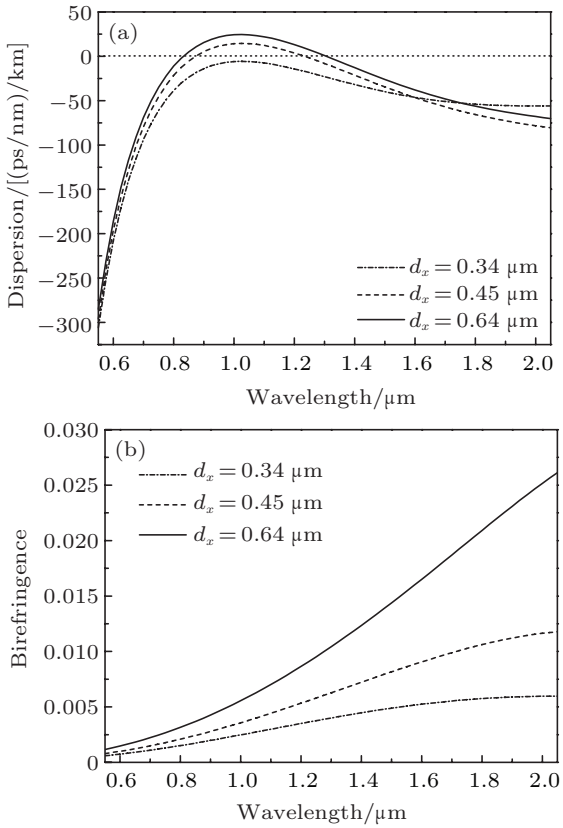


Fig. 3. Influences of the diameter of the air holes on both the upper and lower sides of the cores on the proposed PCF: (a) the dispersion and (b) the birefringence.

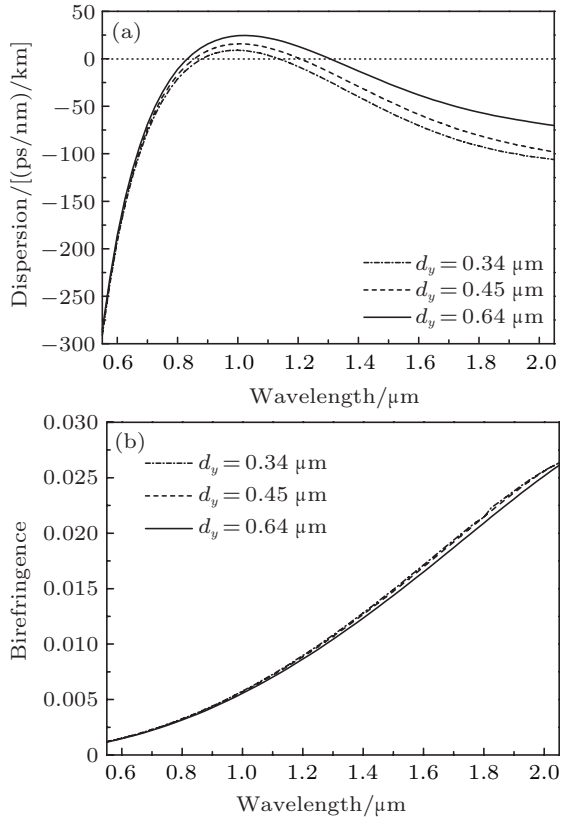


Fig. 4. Influences of the diameter of the air holes on the left and right sides of the cores on the proposed PCF: (a) the dispersion and (b) the birefringence.

Figure 5 shows the changes of the dispersion and the birefringence with different pitches of two adjacent air holes when $d_x = d_y = 0.64$ μm. From Fig. 5 we can find that, when Λ increases, the dispersion curve and the zero dispersion points experience a red shift which leads to the zero dispersion points out of the communication bands and the maximum of the dispersion curve is almost the same, but the birefringence decreases significantly.

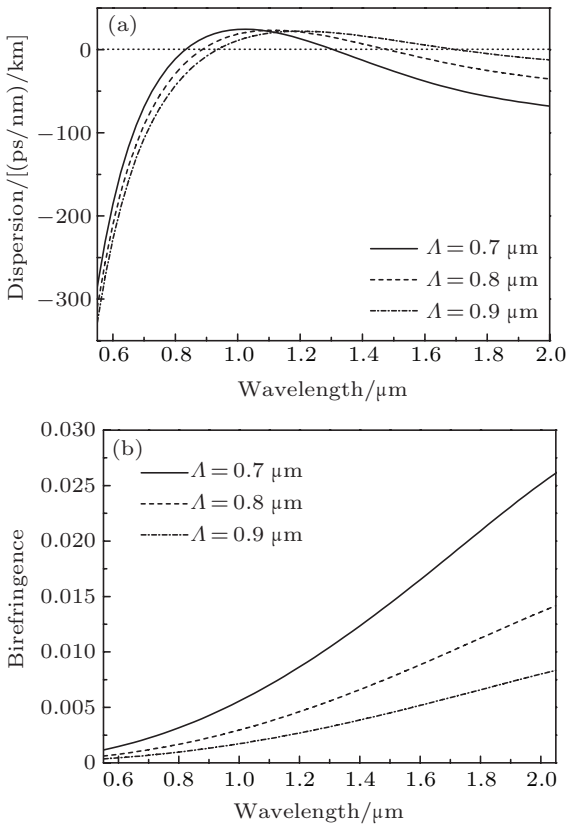


Fig. 5. Influences of the pitch of two adjacent air holes on the proposed PCF: (a) the dispersion and (b) the birefringence.

From the above analyses we can know that the PCF has the best performance when $d_1 = 0.45$ μm, $d_2 = 0.64$ μm, $d_x = d_y = 0.64$ μm, $\Lambda = 0.7$ μm. With these structure parameters, the dispersions of the even mode at x polarization direction are zero both at the wavelengths of $\lambda = 800$ nm and $\lambda = 1310$ nm. The birefringences are up to the order of 10^{-2} which are 1.061×10^{-2} and 1.543×10^{-2} at the wavelengths of $\lambda = 1310$ nm and $\lambda = 1550$ nm, respectively, as is shown in Fig. 6. The changes of the confinement loss with the wavelength are shown in Fig. 7. The confinement loss is low relatively which are 2.41×10^{-9} dB/m and 2.06×10^{-3} dB/m at the wavelengths of $\lambda = 800$ nm and $\lambda = 1310$ nm, respectively. Therefore, the proposed PCF can be applied in the Ti:sapphire femtosecond lasers and the distributed feedback lasers.

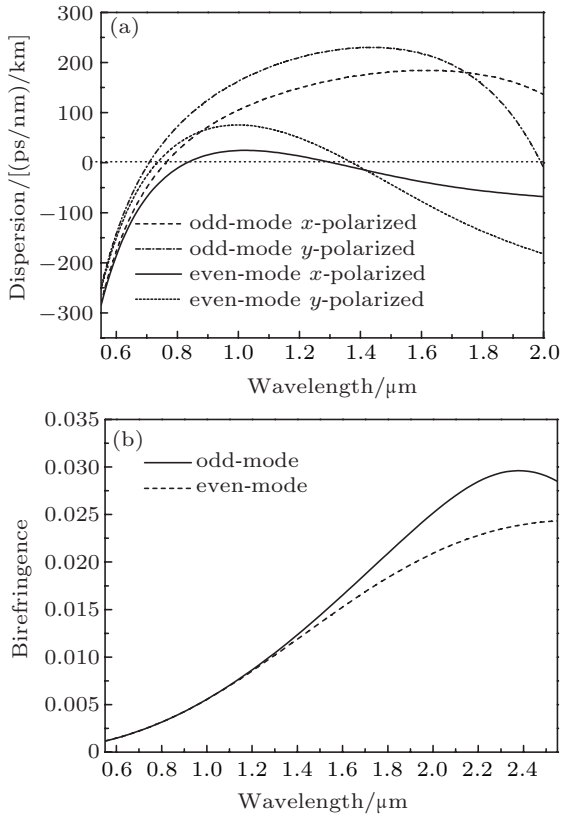


Fig. 6. The dispersion curve (a) and the birefringence curve (b) of the proposed PCF.

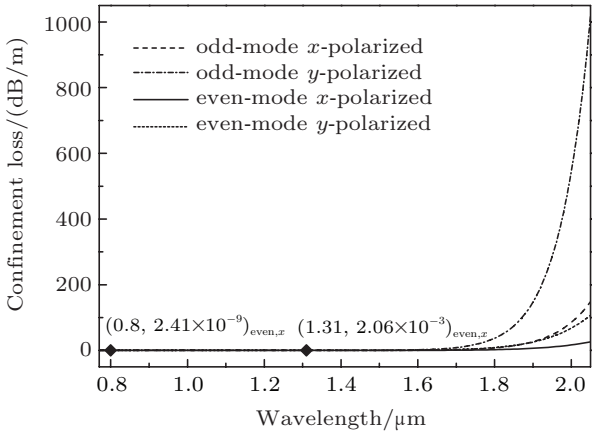


Fig. 7. The variation of the confinement loss as a function of the wavelength for the proposed PCF.

4. Analysis of the transmission characteristics

The proposed PCF has different coupling lengths in two polarization directions. The coupling lengths are 155.08 μm and 146.20 μm for *x*-polarized mode and *y*-polarized mode at the wavelength of $\lambda = 1310$ nm.

Figure 8 shows the relations between the normalized power and the propagation distance. From Fig. 8 we can find that two polarized lights are separated when the propagation is $L = 16L_x = 17L_y = 2.481$ mm. It means that when a beam of light launches into the core *A* of the PCF, the optical waveguide of *y* polarization direction is coupled to the other core *B*, completely, but the optical waveguide of *x* polarization direction is still completely confined in the core *A* at the distance of 2.481 mm. So the PCF with the length of 2.481 mm can be used as a polarization beam splitter for the wavelength of 1310 nm.

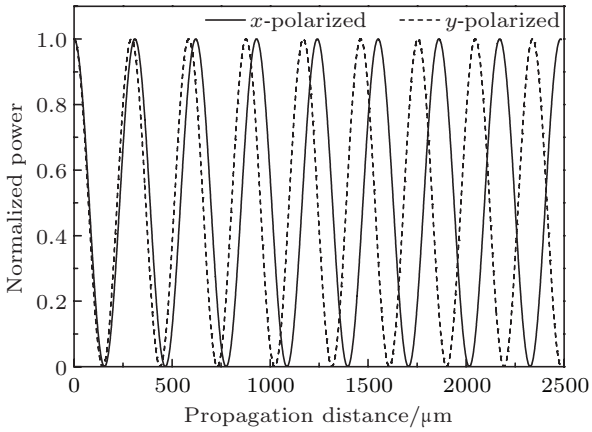


Fig. 8. The normalized power as a function of the propagation distance.

Figure 9 shows the relations between the normalized power and the wavelength of which the propagation distance is $L = 2.481$ mm. It can be found that the normalized powers of *x*-polarized mode and *y*-polarized mode both change periodically.

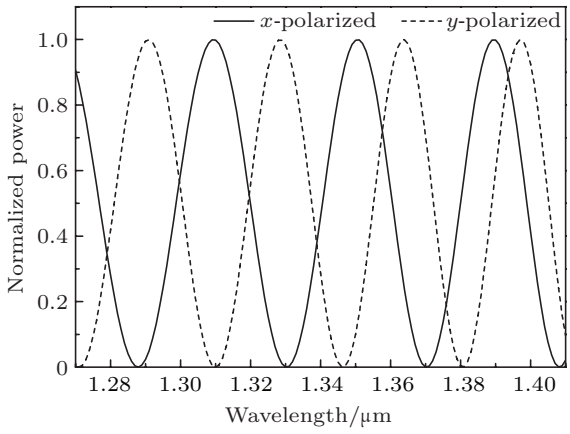


Fig. 9. The changes of the normalized power with the wavelength.

The relations between the extinction ratios and the wavelength are shown in Fig. 10. It can be found that, at the wavelength of $\lambda = 1310$ nm, the largest extinction ratio can reach to −55.3 dB, and the bandwidth where the extinction ratio is better than −10 dB is about 8 nm (from 1306 nm to 1314 nm).

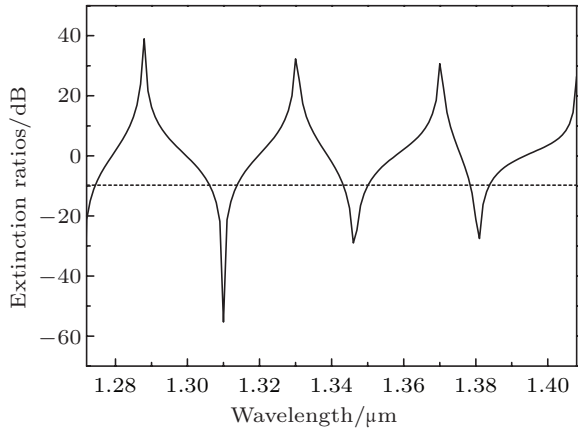


Fig. 10. The changes of the extinction ratios with the wavelength.

5. Conclusions

In this paper, we proposed a dual-core PCF with a simple structure. Then we numerically analyzed the birefringence and the dispersion based on finite element method when the size of the air holes and the pitch of two adjacent air holes are changed. With the parameters of $d_1 = 0.45$ μm, $d_2 = 0.64$ μm, $d_x = d_y = 0.64$ μm, $\Lambda = 0.7$ μm, the proposed PCF has the best characteristics: The zero dispersions points are at the wavelengths of $\lambda = 800$ nm and $\lambda = 1310$ nm which means the PCF can be used in the Ti:sapphire femtosecond lasers and the distributed feedback lasers; The birefringence reaches the order of 10^{-2}, so it means the PCF can be used in polarization-maintaining transmission systems; At the wavelength of $\lambda = 1310$ nm, when the propagation distance is $L = 16L_x = 17L_y = 2.481$ mm, x-polarized light and y-polarized light are separated, so the PCF with the length of 2.481 mm can be used as a polarization beam splitter.

References

[1] Knight J C, Birks T A, Russell P S J and Atkin D M 1996 *Opt. Lett.* **21** 1547

[2] Zhang L, Li S G, Yao Y Y, Fu B, Zhang M Y and ZhengY 2010 *Acta Phys. Sin.* **59** 1101 (in Chinese)

[3] Li H, Wang T J and Huang D X 2004 *Chin. Phys.* **13** 1033

[4] Lou S Q, Wang Z, Ren G B and Jian S S 2004 *Chin. Phys.* **13** 1493

[5] Li S G, Hou L T and Liu X D 2004 *Acta Phys. Sin.* **53** 1880 (in Chinese)

[6] Li S G, Liu X D and Hou L T 2004 *Acta Phys. Sin.* **53** 1873 (in Chinese)

[7] Dong H, Wu C Q and Fu S N 2004 *Chin. Phys.* **13** 1291

[8] Habib M S, Habib M S, Razzak S M A and Hossain M A 2013 *Opt. Fiber Techinol.* **19** 461

[9] Nakajima K, Zhou J, Tajima K, Kurokawa K, Fukai C and Sankawa I 2005 *J. Lightwave Technol.* **23** 7

[10] Matsui T, Nakajima K, Goto Y and Kurashima T 2011 *Opt. Soc. Am.* **50** 6261

[11] Yan H F, Yu Z Y, Tian H D, Liu Y M and Han L H 2010 *Acta Phys. Sin.* **59** 3273 (in Chinese)

[12] Ademgil H and Haxha S 2009 *Opt. Commun.* **282** 2831

[13] Zhang X, Hu M L, Song Y J, Chai L and Wang Q Y 2010 *Acta Phys. Sin.* **59** 1863 (in Chinese)

[14] Kashiwagi M, Saitoh K, Takenaga K, Tangiawa S, Matsuo S and Fujimaki M 2012 *Opt. Lett.* **37** 1292

[15] Guo Y Y and Hou L T 2010 *Acta Phys. Sin.* **59** 4036 (in Chinese)

[16] Hansen T P, Broeng J, Liboriet S E B, Knudsen E, Bjarklev A, Jensen J R and Simonsen H 2001 *Photon. Technol. Lett.* **13** 588

[17] Kazunori S, Kubota H and Kawanishi S 2001 *Opt. Express* **9** 676

[18] Li S G, Liu X D, Zhou G Y and Hou L T 2005 *Chin. Phys. Lett.* **22** 2855

[19] Lou S Q, Wang Z, Ren G B and Jian S S 2004 *Chin. Phys.* **13** 1052

[20] Lou S Q, Ren G B, Yan F P and Jian S S 2005 *Acta Phys. Sin.* **54** 1229 (in Chinese)

[21] Yan F P, Wang L, Mao X Q, Gong T R, Liu P, Tao P L and Peng W J 2010 *Opt. Commun.* **283** 3658

[22] He H M and Li W 2013 *Optik* **124** 5941

[23] Reeves W H, Skryabin D V, Biancalana F, Knight J C, Russell P St J, Omenetto F G, Efimov A and Taylor A J 2003 *Nature* **424** 511

[24] Fang H, Lou S Q, Guo T Y and Jian S S 2007 *Acta Opt. Sin.* **27** 202

[25] Tajima K, Zhou J, Nakajima K and Sato K 2004 *J. Lightwave Technol.* **22** 7

[26] Jiang L H and Hou L T 2010 *Acta Phys. Sin.* **59** 1095 (in Chinese)

[27] Kim S E, Kim B H, Lee C G, Lee S J, Oh K and Kee C S 2012 *Opt. Express* **20** 1385