文章编号:1001 - 9014(2014)03 - 0222 - 05

DOI:10.3724/SP.J.1010.2014.00222

Design of highly birefringent SF57 soft glass PCF with low effective mode area

JIANG Ling-Hong[1*], ZHENG Yi[1], HOU Lan-Tian[2], PENG Ji-Ying[1], ZHENG Kai[1]

(1. Insitute of Laser, School of Science, Beijing Jiaotong University, Beijing 100044, China;
2. State Key Laboratory of Metastable Materials Science and Technology, Yanshan University, Qinhuangdao 066004, China)

Abstract: A simple SF57 soft glass photonic crystal fiber (PCF) with a rhombic array of four elliptical holes in the core region and a hexagonal lattice of elliptical air hole cladding was proposed. The birefringence and effective mode area of the proposed PCF were studied by the full vectorial finite element method with anisotropic perfectly matched layers. A high birefringent SF57 soft glass PCF with low effective mode area has been obtained, which shows good polarization stability and large tolerance to fabrication errors. The proposed PCF has high birefringenceup to 1.01×10^{-1}, low mode areas of 1.52 μm^2 and 1.55 μm^2 for x and y polarizations at 1.55 μm.

Key words: photonic crystal fiber, birefringence, effective mode area, soft glass
PACS: 42.81.-i, 42.81.Gs

高双折射低有效模场面积 SF57 软玻璃光子晶体光纤设计

姜凌红[1*], 郑 义[1], 侯蓝田[2], 彭继迎[1], 郑 凯[1]

(1. 北京交通大学理学院激光所,北京 100044;
2. 燕山大学 亚稳材料制备技术与科学重点实验室,河北 秦皇岛 066004)

摘要:设计了一种包层为椭圆孔排列的六边形结构 SF57 软玻璃光子晶体光纤,在其纤芯区域引入了菱形排列的四个小椭圆孔.利用有限元法模拟了该光子晶体光纤的双折射和有效模场面积,获得了波长 1.55 μm 处双折射为1.01×10^{-1},x 和 y 偏振的有效模场面积分别为 1.52 μm^2、1.55 μm^2 的高双折射低有效模场面积光子晶体光纤.且对该光纤的结构参数进行了实验制作的容差性分析,得到了较大的制作容差对其光纤的双折射影响很小,具有较好的偏振稳定性.

关 键 词:光子晶体光纤;双折射;有效模场面积;软玻璃

中图分类号:TN929.11 **文献标识码**:A

Introduction

Photonic crystal fibers (PCFs)[1] consisting of silica with an array of air holes in the cladding have attracted much attention due to the excellent propagation properties, and they supply diversified applications in optical communication, optical sensing, nonlinear optics and various polarization-sensitive devices etc.[2-3] in recent years. One of the most fruitful aspects of PCFs is their applications as polarization maintaining fiber (PMF). Furthermore, high modal birefringence can be achieved with specially designed PCFs to realize PMF. It is possible to realize birefringent PCFs by altering the air holes in the cladding to the asymmetrical distribution[4-5], or by introducing asymmetric structure in the core region[6]. Furthermore, numerical simulations have indicated that even higher birefringence could be realized by introducing elliptical holes in either cladding or the core region[6-8], and a design using elliptical air holes has been realized experimentally[9].

Nowadays, non-silica compound glasses like soft glasses have been effectively used in formation of PCFs. Stacking, extrusion, drilling and casting all have been used for fabrication of soft glass microstructured optical fibers[10]. Soft glass PCFsoffer unique optical properties, which cannot be provided by silica PCFs, such as high refractive index, high nonlinearity, mid-infrared transmis-

Received date: 2013 - 07 - 15, **revised date**: 2014 - 04 - 27 **收稿日期**:2013 - 07 - 15, **修回日期**:2014 - 04 - 27
Foundation items: Supported by the 973 Program (2010CB327604)
Biography: Jiang Ling-Hong(1983-), female, Jiangxi, Doctor Candidate. Research fields focus on photonic crystal fiber.
* **Corresponding author**: E-mail: no1shajia@163.com

sion, and high rare earth solubility. Recently, soft glass PCFs[11-12] have been reported in the literature to achieve high birefringence at 1.55 μm.

In this paper, we proposed a simple SF57 soft glass PCF with a hexagonal elliptical-hole cladding; there is a rhombic array of four elliptical holes in the fiber core. The main purpose of the proposed PCF structure was to simultaneously achieve high birefringence and low effective mode areaby using the full-vector finite element method with anisotropic perfectly matched layers. Furthermore, we discussed the characteristics of both SF57 soft glass and silica glass PCF with the same structure. Finally, the possibility of fabrication for the proposed PCF was briefly considered.

1 Theory and modeling

By using the full-vector finite element method, the effective refractive index of the proposed PCF was calculated; the birefringenceis expressed as[7]

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

where n_{eff}^{x} and n_{eff}^{y} are the real part of the effective refractive index of two orthogonal polarization fundamental modes. The background material of the proposed PCF is soft glass of type SF57 whose Sellmerier coefficients can be found in Ref. 11.

The cross-sectional view of the proposed SF57 soft glass PCF is shown in Fig. 1. It has four-ring elliptical air holes in the cladding and a rhombic array of four elliptical holes in the core region, the medium one is arranged in a SF57 soft glass. As shown in Fig. 1, elliptical air holes arranged in a triangular array in the cladding can destroy the symmetry to obtain high birefringence, b and a are the major and minor axes of the elliptical air holes, and the ellipticity $\eta = b/a$. The air-hole pitch Λ is taken to be 1.6 μm. Moreover, in order to enhance birefringence, four elliptical holes with a rhombic array are introduced into the core region, which reduce the core diameter, so we can also obtain a small effective mode area. Four elliptical holes with a rhombic array are considered as identical, with the elliptical air-hole major axis b_0 and minor axis a_0; the core region ellipticity $\eta_0 = b_0/a_0$. The pitches between the holes in the vertical and horizontal direction are labeled as Λ_1 and Λ_2, respectively.

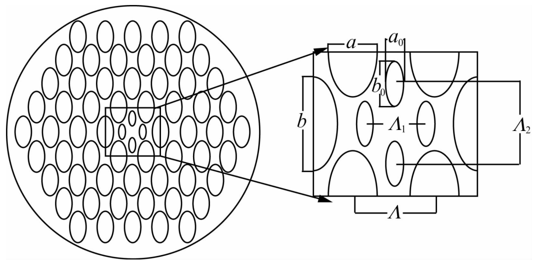

Fig. 1 Cross section of the proposed PCF
图 1 光子晶体光纤横截面图

2 Numerical results and discussion

In general, the birefringence is an important parameter to define the polarization property of fibers. Fig. 2 shows that the birefringence in the short wavelength range is not obviously altered. The value of the birefringence within the longer wavelength band increases with the increase of the ellipticity η. The mode field distribution of PCF with different ellipticity in the short wavelength range is well limited in the core. With longer wavelengths of light accessing to the air hole cladding, the influence of the asymmetry of layer on the fiber birefringence is growing; so the ellipticity has larger effect on the birefringence in the longer wavelength. When the ellipticity η is 2.15, 2.35, and 2.5, the corresponding birefringence can be up to 8.44×10^{-2}, 9.06×10^{-2}, and 9.53×10^{-2} at 1.55 μm, respectively, which is much higher than those obtained in the elliptical hole silica PCF[6-8].

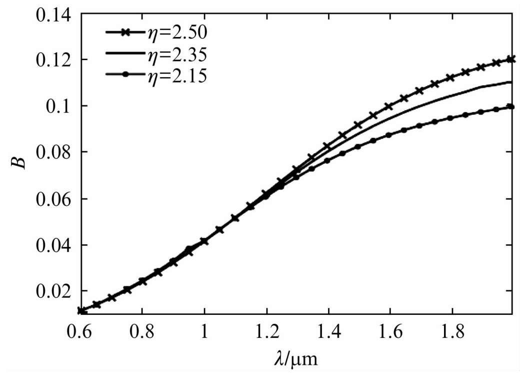

Fig. 2 Variation of birefringence at different ellipticity η
图 2 双折射随不同的椭圆率变化

To obtain higher birefringence, we referenced the cases in which four air holes are arranged in a rhombic array with different Λ_1 and Λ_2. Figure 3 shows the variation of the birefringence at different Λ_1 and Λ_2. As shown in Fig. 3(a), when Λ_1 value keeps constant, the birefringence increases with the decrease of Λ_2. When Λ_2 is 1.4 μm, 1.5 μm, or 1.6 μm, the corresponding birefringence can be up to 1.01×10^{-1}, 9.67×10^{-2}, and 9.31×10^{-2} at 1.55 μm, respectively. Fig. 3(b) shows the birefringence increases with the decrease of Λ_1 as Λ_2 keeps constant. When Λ_1 is 0.86, 0.90, or 0.94, the corresponding birefringence can be up to 1.01×10^{-1}, 9.53×10^{-2} and 8.95×10^{-2} at 1.55 μm, respectively. In agreement with our previous discussion, Fig. 3(c) indicates the birefringence of the fundamental mode under different Λ_2/Λ_1 at 1.55 μm. Smaller value of both Λ_2 and Λ_1 can be used to obtain even higher birefringence. It can be seen that smaller core area could generate larger birefringence, while the intensity distribution of the fundamental mode is not well confined in the core. The birefringence of 1.06×10^{-1} at 1.55 μm under $\Lambda_1 = 0.8$ μm and $\Lambda_2 = 1.4$ μm is larger at the expense of slightly poorermode field distribution. In order to gain higher birefringence and a better mode field distributionin a wavelength range around 1.55 μm, here we select the value of $\Lambda_1 = 0.86$ μm, $\Lambda_2 = 1.4$ μm.

Next, we referenced the case in which four air holes were arranged in a rhombic array with $\Lambda_1 = 0.86$ μm, $\Lambda_2 = 1.4$ μm, so that the birefringence would be mainly effected by the shape of the elliptical holes in the core region. To focus on the impact of the hole shape on the birefringence, the size of the air holes in the cladding is kept the same, while a_0 and b_0 are varied. As shown in Fig. 4, the birefringence increases with a_0 increasing as b_0 is fixed, while decrease with the decrease of b_0 as a_0 is uniform. The asymmetry of the proposed PCF increases with the increase of the elliptical hole size in the core region.

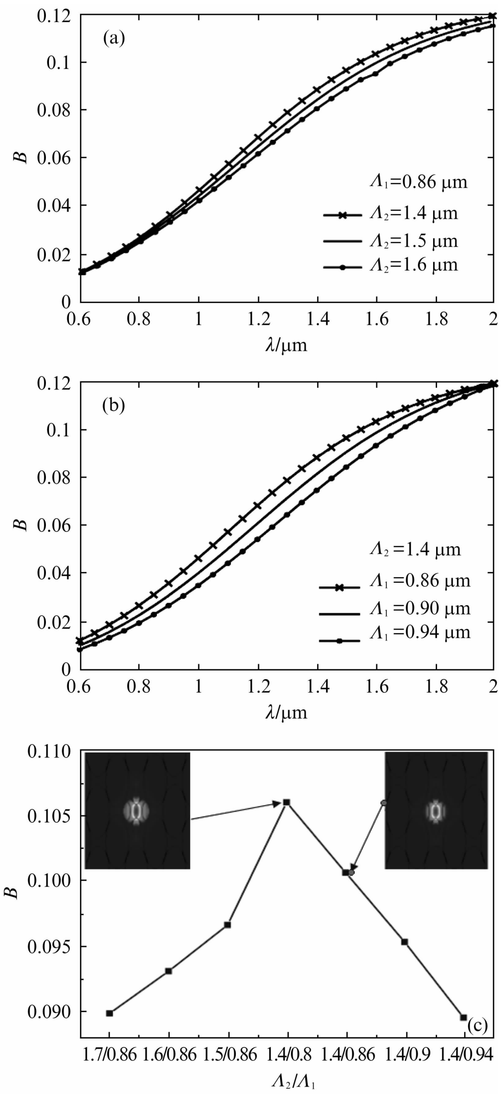

Fig. 3 Variation of the birefringence under different (a) Λ_2, (b) Λ_1 and (c) Λ_2/Λ_1.
图 3 双折射随着不同的(a)Λ_2, (b)Λ_1 and (c)Λ_2/Λ_1 变化

Figure 5 shows the birefringence and effective mode areain SF57 soft glass PCF and silica PCF with the same structure parameter of $\Lambda_1 = 0.9$ μm, $\Lambda_2 = 1.4$ μm, $\Lambda = 1.6$ μm, $\eta = 2.5$, $a_0 = 0.3$ μm, $b_0 = 0.8$ μm. As shown in Fig. 5(a), the difference of birefringence in SF57 soft glass PCF and silica PCF become larger as the wavelength increases. The birefringence in SF57 soft glass PCF and silica PCF can be up to 9.53×10^{-2} and 4.57×10^{-2} at 1.55 μm, respectively. The birefringence of SF57 soft glass PCF is almost 2 times higher than that of silica PCF, so the SF57 soft glass optical fiber is more suitable for application in polarization maintaining PCF. Fig. 5(b) shows that x-polarized mode area of SF57 soft glass PCF and silica PCF are 1.34 μm^2 and 2.85 μm^2, and y-polarized mode area of SF57 soft glass PCF and silica PCF are 1.55 μm^2 and 2.77 μm^2 at 1.55 μm, respectively. The mode area of silica PCF is over 2 times higher than that of SF57 soft glass PCF, so the soft glass is more suitable for the application in highly nonlinear PCF.

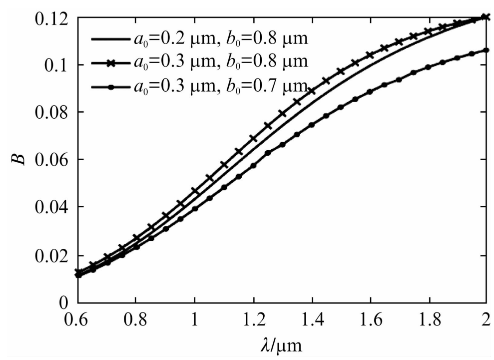

Fig. 4 Variation of birefringence with different a_0 and b_0
图 4 双折射随不同的纤芯椭圆大小 a_0, b_0 的变化

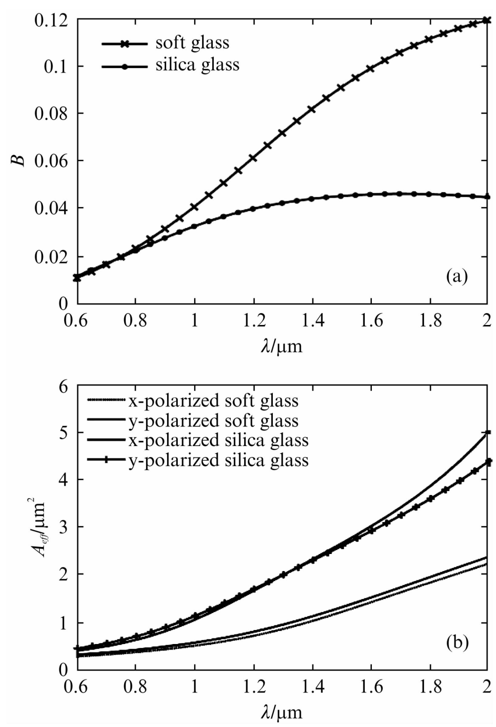

Fig. 5 Variation of (a) B, (b) A_{eff} for both soft glass and silica PCF under with the same structure parameter
图 5 相同结构参数下的软玻璃和石英玻璃光子晶体光纤(a)双折射,(b)有效模场面积的变化

According to the discussion above, in order to gain higher birefringence and lower effective mode, the structure parameters for the proposed soft glassare selected to be $\eta = 2.5$, $\Lambda_1 = 0.86$ μm, $\Lambda_2 = 1.4$ μm, $a_0 = 0.3$ μm, $b_0 = 0.8$ μm. Fig. 6(a) shows that the birefringence of the soft glass PCF is as high as 1.01×10^{-1} at 1.55 μm which is greater than the high birefringence of 4.50×10^{-2} of soft glass PCF with liquid crystal core[11]. As shown in Fig. 6(b), x- and y-polarized effective mode areas are low to 1.52 μm^2 and 1.55 μm^2 at 1.55 μm, respectively. Figs. 7(a) and 7(b) show the electric field distribution of x- and y- polarized fundamental mode for the proposed PCF withthe parameter of $\Lambda_1 = 0.86$ μm, $\Lambda_2 = 1.4$ μm, $\Lambda = 1.6$ μm, $\eta = 2.5$, $a_0 = 0.3$ μm, $b_0 = 0.8$ μm at 1.55 μm, respectively. The mode field of x and y polarization are well confined in the fiber core.

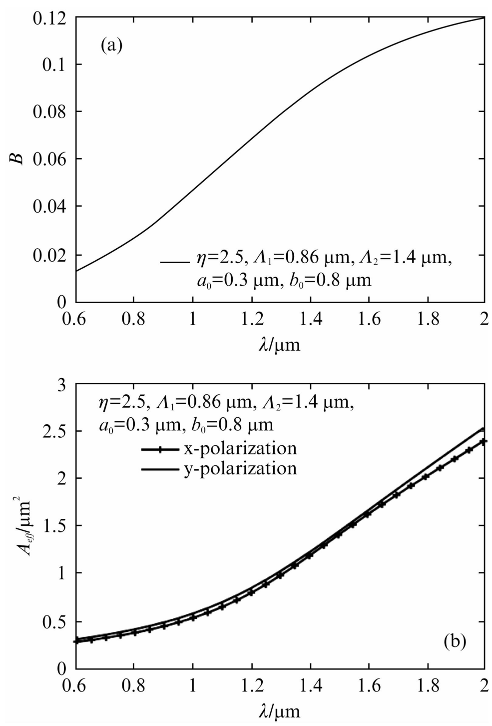

Fig. 6　Variation of (a) B, (b) A_{eff} as a function of wavelength
图 6　(a)双折射,(b)有效模场面积随波长的变化

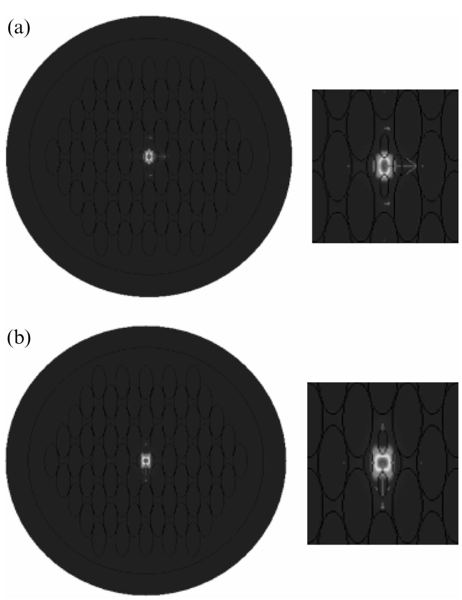

Fig. 7　Electric field distribution of (a) x-, (b) y-polarized fundamental mode for the proposed PCF at 1.55 μm
图 7　波长 1.55 μm 时 (a)x 偏振,(b)y 偏振的模场分布图

Finally, we briefly considered the possibility of fabrication for the proposed PCF. In a standard fiber drawing, 1% variation of structural parameter occurs unavoidably during the fabrication process. It is the limited precision that is the only way to guarantee the parameters. Therefore, we deduced that all the geometric parameters are varied in ±5% from the optimum values. Tab. 1 shows that 5% of a hole's deviation from its designed position, either in the cladding or core region, can lead to at most 5.7% changes in the birefringence. It is assumed that the proposed PCF has good tolerance of this novel design to fabrication errors. In the fabrication process, the elliptical holes may be sensitive to collapse and to change into circular on due to the surface tension. To overcome these problems, new methods such as extrusion, drilling and casting have been introduced for fabrication such PCFs.

Table 1　Birefringence tolerance for the optimum structural parameters fluctuations at 1.55 μm
表 1　波长 1.55 μm 处光纤结构参数变化后的双折射容差比

Structure parameters variation	B_0	$(B-B_0)/B$
$\Delta\eta/\eta = +5\%$	0.105 814	−5.18%
$\Delta\eta/\eta = -5\%$	0.095 567	+5.01%
$\Delta\eta_0/\eta_0 = +5\%$	0.105 755	−5.12%
$\Delta\eta_0/\eta_0 = -5\%$	0.094 873	+5.69%
$\Delta\Lambda_1/\Lambda_1 = +5\%$	0.095 867	+4.68%
$\Delta\Lambda_1/\Lambda_1 = -5\%$	0.104 901	−4.27%
$\Delta\Lambda_2/\Lambda_2 = +5\%$	0.097 739	+2.84%
$\Delta\Lambda_2/\Lambda_2 = -5\%$	0.103 480	−2.87%

3　Conclusions

In this paper, a highly birefringent SF57 soft glass PCF with low effective mode area was proposed and analyzed by FEM with PML. By introducing a rhombic array of four elliptical holes into the fiber core region, which is not only to obtain higher birefringence but also achieve lower effective mode area. In addition, we have also compared SF57 soft glass PCF with silica PCF with the same structure, and then find out that soft glass PCF has higher birefringence and smaller effective mode area than those of silica PCF. Hence soft glass PCFs possess high potential as PMF. With the parameter of $\Lambda_1 = 0.86$ μm, $\Lambda_2 = 1.4$ μm, $\Lambda = 1.6$ μm, $\eta = 2.5$, $a_0 = 0.3$ μm, $b_0 = 0.8$ μm, the birefringence of the proposed SF57 soft glass PCF is as high as 1.01×10^{-1}, and x- and y-polarized effective mode areas are 1.52 μm^2 and 1.55 μm^2 at 1.55 μm, respectively. The proposed PCF has good tolerance of this novel design to fabrication errors, and therefore may be realized very close to theoretical design. The obtained results make a contribution to the production and application of optical devices based on such photonic crystal fibers.

References

[1] Knight J C. Photonic crystal fibres[J]. *Nature*, 2003, **424**(6950): 847-851.
[2] ZHAO Chun-Liu, YANG Xiu-Feng, LU Chao, *et al*. Temperature-in-

sensitive interferometer using a highly birefringent photonic crystal fiber loop mirror[J]. *IEEE Photonics Technol. Lett.*, 2004, **16**(11): 2535-2537.

[3] CUI Hai-Yan, HOU Lan-Tian, HAN Ying. Generation of infrared ultra-wide band continuum spectrum photonic crystal fiber[J]. *J. Infrared Millim. Waves*, 2010, **29**(6): 445-451.

[4] CAO Yue, LI Rong-Min, TONG Zheng-Rong. Invest-igation of a new kind of high birefringence photonic crystal fiber[J]. *Acta Phys. Sin.*, 2013, **62**(8): 084215-1-6.

[5] LI De-Yue, ZHOU Gui-Yao, XIA Chang-Ming, *et al*. Theoretical investigation of photonic crystal fiber with highly nonlinear and birefringent[J]. *Chinese J. Lasers*, 2012, **39**(11): 1105003-1-6.

[6] CHEN Da-Ru, SHEN Lin-Fang. Ultrahigh birefringent photonic crystal fiber with ultralow confinement loss[J]. *IEEE Photon. Technol. Lett.*, 2007, **19**(4): 185-187.

[7] ZHANG Ya-Ni. Design and optimization of high-birefringence low-loss crystal fiber with two zero-dispersion wavelengths for nonlinear effects [J]. *Appl. Opt.*, 2011, **50**(25): 125-130.

[8] YUE Yang, KAI Gui-Yun, WANG Zhi, *et al*. Highly birefringent elliptical-hole photonic crystal fiber with squeezed hexagonal lattice[J]. *Opt. Lett.*, 2007, **32**(5): 469-471.

[9] Issa N A, van Eijkelenborg M A, Fellew M, *et al*. Fabrication and study of microstructured optical fibers with elliptical holes[J]. *Opt. Lett.*, 2004, **29**(12): 1336-1338.

[10] Ebendorff-Heidepriem H, Monro T M. Extrusion of complex preforms for microstructured optical fibers[J]. *Opt. Express*, 2007, **15**(23): 15086-15092.

[11] Hameed M F O, Obayya S S A. Modal analysis of a novel soft glass photonic crystal fiber with liquid crystal core[J]. *J. LightwaveTechn.* 2012, **30**(1): 96-102.

[12] FU Bo, LI Shu-Guang, YAO Yan-Yan, *et al*. Supercontinuum generation with high birefringence SF6 soft glass photo-niccrystal fibers[J]. *Chinese Phys. Lett.*, 2010, **27**(7): 74209-74212.