第 36 卷 第 3 期
2009 年 3 月

中 国 激 光
CHINESE JOURNAL OF LASERS

Vol. 36, No. 3
March, 2009

文章编号: 0258-7025(2009)03-0635-05

Broadband directional coupler based on asymmetric dual-core photonic crystal fiber

Mingyang Chen(陈明阳)[1*], Yongkang Zhang(张永康)[1], Yuanfeng Zhu(祝远锋)[1], Yanqun Tong(佟艳群)[1], and Jun Zhou(周骏)[1,2]

[1] *Department of Optical Engineering, School of Mechanical Engineering, Jiangsu University, Zhenjiang, Jiangsu* 212013, *China*

[2] *Faculty of Science, Ningbo University, Ningbo, Zhejiang* 315211, *China*

* *Corresponding author: miniyoung@163.com*

Received November 5, 2008; revised December 31, 2008

Abstract A novel broadband directional coupler based on an asymmetric dual-core photonic crystal fiber (PCF) is proposed. The asymmetry in the fiber is introduced by the enlargement of one air-hole in dual-core PCF. Numerical investigation demonstrate that broadband directional coupling with spectral width as large as 370 nm and polarization-dependent loss and uniformity lower than 0.2 and 0.5 dB, respectively, can be achieved. In addition, the proposed fiber shows large tolerance to the variation of the fiber parameters. In particular, the fiber length allows at least 10% derivation from the proposed fiber length of 7.7 mm.

Key words directional couplers; photonic crystal fiber; asymmetric-core optical fiber; polarization-dependent loss; uniformity

CLCN: TP212.14 **Document Code:** A **doi:** 10.3788/CJL20093603.0635

1 Introduction

Photonic crystal fiber (PCF)[1~4], a novel kind of optical fiber composed of air-holes in the background of silica, has been put forward as a novel method for fabricating optical fiber couplers[5]. Applications of dual-core PCFs as polarization splitters [6~9], wavelength division multiplex components [10], filters [11], and dispersion compensations[12], have been proposed. However, the application of dual-core PCF as a directional coupler is generally difficult due to the fact that the coupled energy in dual-core PCF is generally polarization- and wavelength-dependent, as a result of the high index contrast. Therefore, directional couplers based on PCFs generally have low bandwidths and high polarization losses. Recently, a novel design of broadband directional coupler has been proposed by Lægsgaard *et al.* [13] The twin-core PCF forms the basis of an unusually broadband directional coupler, because the coupling length curve of the fiber can be made extraordinarily flat over an extremely broad frequency range. The design shows the great versatility of PCF couplers, because it's not easy to realize broadband coupling in a conventional optical fiber. However, the down-doped core in the fiber coupler leads to the deformation of the mode field, which induces additional insertion losses.

In this paper, a novel dual-core PCF coupler is proposed and the cores of the fiber are designed to be asymmetric. Asymmetry is introduced in the otherwise dual-core PCF with two-fold symmetries. The proposed coupler could work as a broadband directional coupler with large tolerance to the fiber length. The coupler also shows polarization-dependent loss (PDL) lower than 0.2 dB with spectral width as large as 370 nm.

This work was supported by the Senior Talent Foundation of Jiangsu University (06JDG062), the Natural Science Foundation of the Jiangsu Higher Education Institutions of China (08KJB510001), Qianjiang Talent Project of Zhejiang Province (2007R10015), the Science Foundation of Ningbo (2008A610001), and the National Natural Science Foundation of China (10574058 and 50735001).

2 Numerical investigations

The configuration of the fiber is shown in Fig. 1. The fiber is characterized by the centre-to-centre distance of the two nearest air-holes Λ (pitch) and the normalized rod diameter d/Λ. In addition, the index of pure silica is set as $n_c = 1.45$ and the dispersion of silica is ignored. The configuration shows here is very similar to a conventional hexagonal-structure PCF except that an air-hole adjacent to one of the cores is enlarged. The diameter of the enlarged air-hole is denoted as d_2. The values of the parameters are set as $d/\Lambda=0.3$, $d_2/\Lambda=0.47$, and $\Lambda=9.3\ \mu$m, respectively.

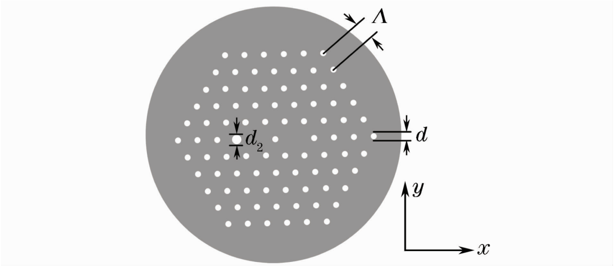

Fig.1 Cross-section of the proposed PCF coupler

To investigate the transmission properties of the proposed fiber, a full-vectorial finite-difference beam propagation method [14] with transparent boundary condition [15] is applied. The power transfer as a function of fiber length for the symmetric-core PCF ($d_2/\Lambda=0.3$) and the proposed PCF coupler ($d_2/\Lambda=0.47$), at the operating wavelength of 1.55 μm, are shown in Fig.2(a) and (b) respectively. In the symmetric core PCF coupler, nearly 100% energy can be transferred between the two cores, therefore, when used as a directional coupler, the fiber length should be chosen as $L_d=L_c/2$, where L_c is the coupling length of the fiber. The coupling lengths of the x- and y-polarized states in the fiber have been shown in Fig.2(a) and is denoted as L_{cx} and L_{cy}, respectively. However, the first derivative of the curve is the largest when the propagation distance is L_{dx} (or L_{dy}), where L_{dx} and L_{dy} denote the coupler lengths of the x- and y-polarized states, respectively. Therefore, low bandwidth and low tolerance to the fiber length are expected. When asymmetry is introduced into the fiber, the coupling efficiency will be reduced, owning to the index mismatch. By appropriate selecting the diameter of the enlarged air-hole, we can control the amount of power transferred between the two cores in the asymmetric PCF coupler. As shown in Fig.2 (b), by setting the diameter of the enlarged air-hole to be $d_2/\Lambda=0.47$, only about 50 % of power can be transferred between the two cores of the coupler. By setting the length of the coupler L_c to be L_d, the field launching into one of the cores will exit equally from the two cores. Also a low polarization dependent coupling is found in the fiber. In fact, the difference between the coupling lengths of the two polarized states is lower than 0.01 mm. Therefore, low PDL is expected in the proposed fiber coupler. In contrast to the asymmetric-core PCF, the coupling length difference for the symmetric core PCF is 0.6 mm. Since the fiber length of the asymmetric-core PCF is set at where the first derivative of the normalized output power is zero, the deviation of fiber length from the optimal value only leads to very small influence on the output power distribution in the two cores. Therefore, the proposed fiber could have large tolerance to the fiber length, as will be demonstrated in the next section.

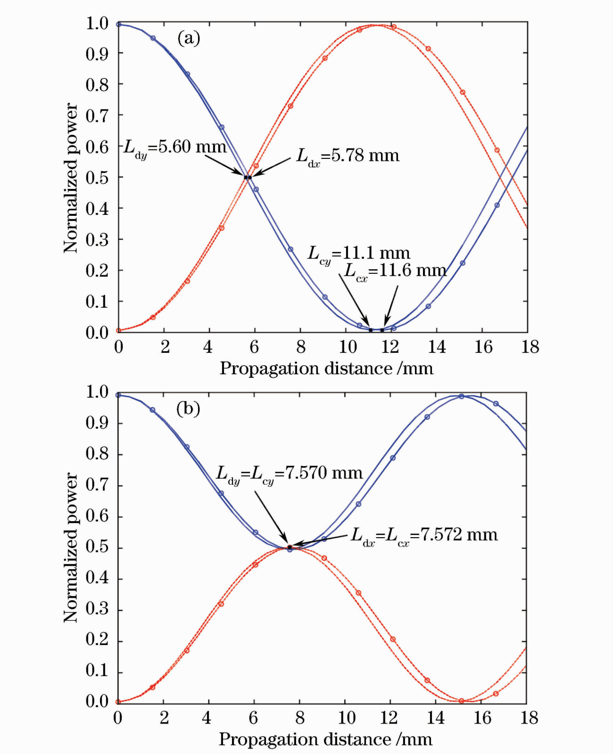

Fig.2 Power transfers in the two cores of the symmetric core PCF ($d_2/\Lambda=0.3$) (a) and the proposed PCF coupler ($d_2/\Lambda=0.47$) (b). The solid and dashed curves denote the powers in the left and right cores, respectively. The curves with and without circles denote the powers in the x- and y-polarized states, respectively

Insertion loss of the fiber coupler is defined as the ratio of the optical power launched at the input port of the coupler to the optical power from any single output port, expressed in dB. The PDL is defined as the difference between the insertion losses of the two polarized modes in the same output port. The output power of the two cores of the fiber as a function of the operating wavelength is shown in Fig. 3. If the available bandwidth is defined as the wavelength range within which the uniformity is lower than 0.5 dB, that is, the insertion losses of the two cores are in the range of 3.0 ± 0.25 dB, and PDL is lower than 0.2 dB, they can cover the wavelength range from 1.41 to 1.78 μm. Therefore, the bandwidth can be as large as 370 nm. If PDL lower than 0.1 dB is required, the wavelength range can still cover from 1.41 to 1.66 μm, and the bandwith is 250 nm. The power transferring as a function of wavelength for the symmetric-core PCF coupler with $L = 5.7$ mm is plotted in Fig. 4. The coupler shows available bandwidth lower than 40 nm with the uniformity lower than 0.5 dB and almost invariant PDL of 0.2 dB for the entire bandwidth range.

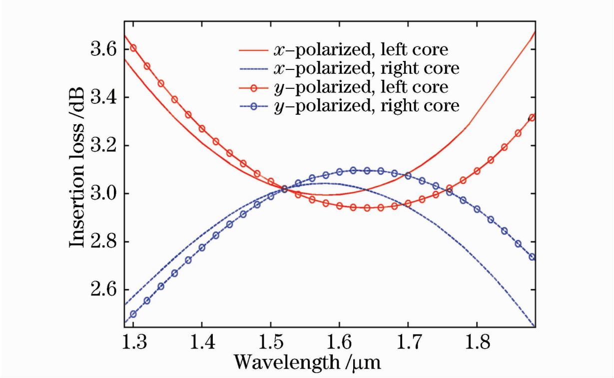

Fig. 3　Insertion losses of the proposed fiber coupler as a function of wavelength with fiber length $L_d = 7.7$ mm

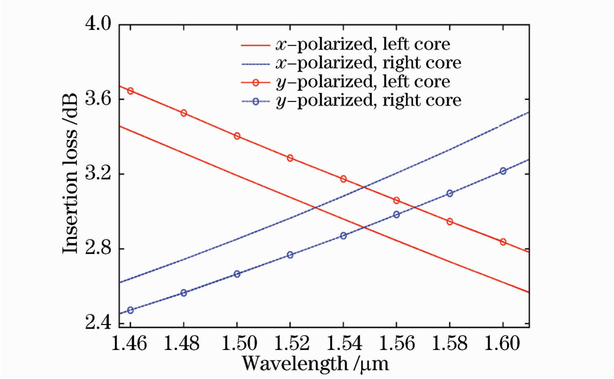

Fig. 4　Insertion losses of the symmetric fiber coupler as a function of wavelength with fiber length $L_d = 5.7$ mm

Figures 5(a) and (b) show the power transferring in the two cores of the symmetric dual-core PCF coupler and the proposed coupler with the operating wavelength λ set as 1.45, 1.55 and 1.65 μm. When the operating wavelength is longer or shorter than the center wavelength of 1.55 μm, there's large difference between the output power in the two cores of the symmetric-core coupler. Therefore, the bandwidth is limited. For the proposed coupler, the coupling length increases when the operating wavelength reduces, but at the same time, the coupling coefficient reduces. On the other hand, when the operating wavelength increases, the coupling length reduces, but the coupling coefficient increases. As a result, the difference between the output power in the two cores is still small for longer and shorter wavelengths. This explains why the wide operating bandwidth can be achieved in the proposed coupler.

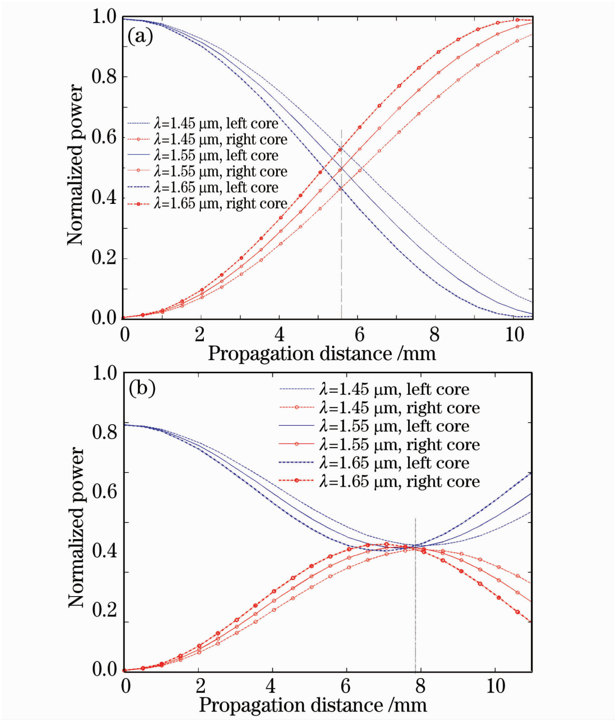

Fig. 5　Power transfers in the cores of the symmetric-core PCF (a) and the proposed fiber (b)

3　Discussions

One important issue about dual-core PCFs is the tolerance of the structure parameters. Numerical investigation demonstrates that the proposed fiber shows low sensitivity to the variation of fiber parameters. We will present here the investigation on the variation of the diameter of the enlarged air-hole and the fiber length on the properties of the proposed coupler.

Figure 6 shows the output power in the cores of a fiber with the normalized diameter of the enlarged air-hole $d_2/\Lambda = 0.465$ and 0.475, respectively. The reduction of the air-hole diameter leads to the movement of available wavelength region to short wavelength, whereas the increase of the air-hole diameter leads to the movement of available wavelength region to long wavelength. The wavelength ranges where the insertion loss is within 3 ± 0.25 dB and the PDL is lower than 0.2 dB are [1.374, 1.600] μm and [1.448, 1.697] μm for the fiber with $d_2/\Lambda = 0.465$ and 0.475, respectively. In either case, it covers the wavelength of 1.55 μm. This means that the proposed fiber allows at least a tolerance of ±1% for the large air-hole in size, that is, the air-hole should allow a tolerance of ±46.5 nm in diameter. It is now possible to manufacture the microstructure in air-glass PCF to accuracy of 10 nm on the scale of 1 μm [1]. Therefore, the proposed fiber can be fabricated by the up-to-date techniques.

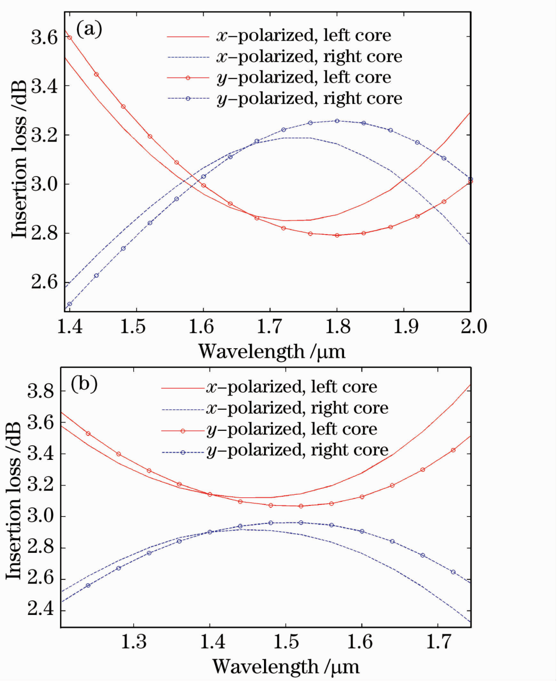

Fig.6 Insertion losses of the proposed fiber coupler as a function of wavelength with $L_d=7.7$ mm and enlarged air-hole normalized diameter d_2 = 0.465 (a) and 0.475 (b), respectively

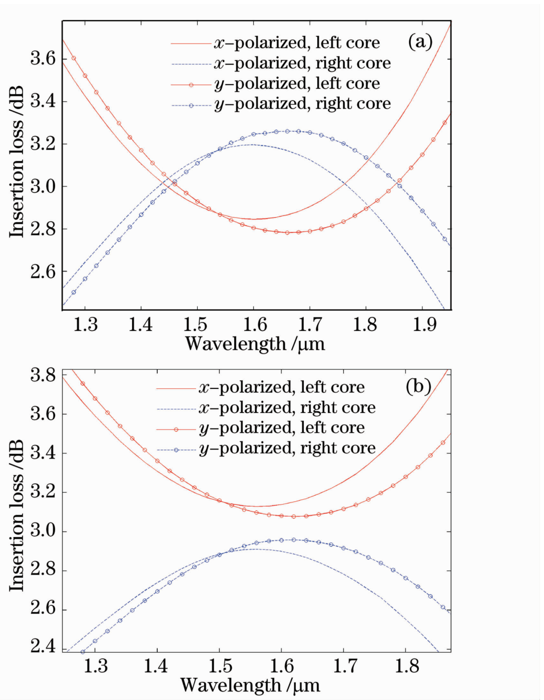

Fig.7 Insertion losses of the proposed fiber as a function of wavelength with fiber length $L_d=6.9$ mm (a) and 8.5 mm (b), respectively

The output power in the cores of a proposed fiber with $d_2/\Lambda=0.47$ are shown in Fig.7 with the fiber length $L_d=6.9$ mm and 8.5 mm, respectively. As shown in the figure, when a short fiber length is chosen, the centre wavelength of 1.55 μm is within the range, in fact, lower PDL is found. The available wavelength range is from 1.502 to 1.82 μm with the PDL lower than 0.1 dB and uniformity lower than 0.5 dB for the fiber with $L_d=6.9$ mm. And the available wavelength range is from 1.34 to 1.586 μm with the PDL lower than 0.13 dB and uniformity lower than 0.25 dB for the fiber with $L_d=8.5$ mm. Therefore, if the fiber length L_d is chosen to be 7.7 mm, we can allow a variation of at least ±10% deviation of the fiber length.

4 Conclusion

We proposed the design of a directional coupler based on a novel PCF configuration. The coupler is realized by the deliberately introduced asymmetry in the dual-core PCF. The main advantages of the proposed fiber are the large bandwidth, low polarization loss, and short fiber length. The fiber contains a core similar to that of a conventional PCF, which leads low splice loss. In addition, the large tolerances to the fiber length and air-hole diameter allow the fabrication of the fiber by the up-to-date techniques.

References

1 P. S. J. Russell. Photonic crystal fibers[J]. *J. Lightwave Technol.*, 2006, **24**(12): 4729～4749

2 Gong Taorong, Yan Fengping, Wang Lin *et al.*. Analysis of properties of high birefringence photonic crystal fibers[J]. *Chinese J. Lasers*, 2008, **35**(4): 559～562
龚桃荣,延凤平,王 琳 等. 高双折射光子晶体光纤特性分析[J]. 中国激光, 2008, **35**(4): 559～562

3 Wu Ming, Liu Hairong, Huang Dexiu. Dispersion property in highly nonlinear photonic crystal fiber[J]. *Acta Optica Sinica*, 2008, **28**(3): 539～542
吴 铭,刘海荣,黄德修. 高非线性光子晶体光纤色散特性的研究[J]. 光学学报, 2008, **28**(3): 539～542

4 Tan Xiaoling, Geng Youfu, Wang Peng *et al.*. Propagation properties of the octagonal photonic crystal fiber[J]. *Chinese J. Lasers*, 2008, **35**(5): 729～733
谭晓玲,耿优福,王 鹏 等. 八角格子光子晶体光纤的传输特性[J]. 中国激光, 2008, **35**(5): 729～733

5 Weimin Sun, Xiaoqi Liu, Fenghua Fu *et al.*. Fabrication of fiber-embedded multi-core photonic crystal fibers[J]. *Chin. Opt. Lett.*, 2008, **6**(10): 715～717

6 L. Zhang, C. Yang. Polarization-dependent coupling in twin-core photonic crystal fibers[J]. *J. Lightwave Technol.*, 2004, **22**(5): 1367～1373

7 M. Y. Chen, R. J. Yu. Coupling characteristics of dual-core rectangular lattice photonic crystal fibers[J]. *J. Opt. A: Pure Appl. Opt.*, 2004, **6**(8): 805～808

8 Y. Yue, G. Kai, Z. Wang, C. Zhang *et al.*. Broadband single-polarization single-mode photonic crystal fiber coupler[J]. *IEEE Photon. Technol. Lett.*, 2006, **18**(19): 2032～2034

9 N. Florous, K. Saitoh, M. Koshiba. A novel approach for desig-

ning photonic crystal fiber splitters with polarization-independent propagation characteristics[J]. *Opt. Express*, 2005, **13**(19): 7365～7373

10 M. Y Chen, J. Zhou. Polarization-independent splitter based on all-solid silica-based photonic crystal fibers[J]. *J. Lightwave Technol.*, 2006, **24**(12): 5082～5086

11 X. Sun. Wavelength-selective coupling of dual-core photonic crystal fiber with a hybrid light-guiding mechanism[J]. *Opt. Lett.*, 2007, **32**(17): 2484～2486

12 Honghua Wang, Wenrui Xue, Wenmei Zhang. Negative dispersion properties of photonic crystal fiber with dual core and composite lattice[J]. *Acta Optica Sinica*, 2008, **28**(1): 27～30
王红华,薛文瑞,张文梅. 双芯复合格点光子晶体光纤的负色散特性[J]. 光学学报, 2008, **28**(1): 27～30

13 J. Lægsgaard, O. Bang, A. Bjarklev. Photonic crystal fiber design for broadband directional coupling[J]. *Opt. Lett.*, 2004, **29**(21): 2473～2475

14 W. P. Huang, C. L. Xu. Simulation of three-dimensional optical waveguides by a full-vectorbeam propagation method[J]. *IEEE J. Quantum Electron.*, 1993, **29**(10): 2639～2649

15 R. Hadley. Transparent boundary condition for the beam propagation method[J]. *IEEE J. Quantum Electron.*, 1992, **28**(1): 363～370