Coupling characteristics of three-core photonic crystal fiber couplers

Ming-Yang Chen¹, Yong-Kang Zhang¹, Jun Zhou¹ and E Y B Pun²

¹ Department of Optical Engineering, School of Mechanical Engineering, Jiangsu University, Zhenjiang 212013, Jiangsu Province, People’s Republic of China
² Department of Electronic Engineering, City University of Hong Kong, Kowloon, Hong Kong, People’s Republic of China

E-mail: miniyoung@163.com

Received 6 June 2008, accepted for publication 13 November 2008
Published 4 December 2008
Online at stacks.iop.org/JOptA/11/015102

Abstract
The coupling characteristics of a three-core photonic crystal fiber (PCF) and its application as a broadband directional coupler are investigated. Numerical investigations demonstrated that broadband directional coupling with spectral width as large as 425 nm and polarization-dependent loss lower than 0.06 dB could be achieved in the proposed fiber coupler. In addition, the proposed fiber shows large tolerance to the variation of the fiber parameters. In particular, the fiber allows at least 4% deviation of the air-hole diameters and 10% deviation from the proposed length of 27 mm.

Keywords: directional coupler, photonic crystal fibre, polarization-dependent loss, beam propagation method

(Some figures in this article are in colour only in the electronic version)

1. Introduction

An optical fiber coupler is a passive device, which is widely used in optical fiber communication systems, fiber sensor systems, fiber measurement technology, and so on. The appearance of photonic crystal fibers (PCFs) has enabled a new method of designing fiber couplers. Applications of PCF couplers as polarization splitters [1–3], wavelength division multiplex components [4–6], and filters [7] have been proposed. However, the fabrication of a PCF directional coupler is generally difficult; this is due to the fact that the coupling strength is generally polarization and wavelength dependent, as a result of high index contrast. Therefore, PCF couplers generally have limited bandwidths and also high polarization losses. Recently, a novel design of a broadband directional coupler has been proposed by Lægsgaard et al [8]. The twin-core PCF forms the basis of an unusually broadband directional coupler because of the vanishing first derivative of the coupling length. However, the introduced down-doped core in the fiber leads to the deformation of the mode field, which induces additional insertion losses.

In this paper, a novel three-core PCF coupler is proposed. The proposed coupler could work as a broadband directional coupler with large tolerance to the fiber length. The coupler also shows a polarization-dependent loss (PDL) lower than 0.06 dB with spectral width as large as 425 nm.

2. Results and discussion

The configuration of the proposed fiber is shown in figure 1. The fiber is characterized by the center-to-center distance of the two nearest air-holes \( \Lambda \) (pitch) and the normalized air-hole diameter \( d/\Lambda \). The values of the parameters are set as \( \Lambda = 15.5 \, \mu m \) and \( d/\Lambda = 0.3 \), respectively. The index of pure silica is set as \( n_c = 1.45 \), and the dispersion of silica is ignored. The center wavelength is assumed to be 1.55 \( \mu m \). We use a small air-hole diameter so that the polarization effects of the coupler can be reduced [4]. A large pitch is chosen so that the confinement losses of the fundamental mode could be sufficiently low. In fact, the confinement losses of the fundamental mode are always lower than 0.2 dB/m for the wavelength range 1–2 \( \mu m \). We can reduce the losses further by increasing the number of air-holes in the cladding, but generally this is not needed, because the length of the proposed fiber coupler is very short (on the order of tens of millimeters).
To investigate the transmission properties of the proposed fiber, a full-vectorial finite-difference beam propagation method [9] with transparent boundary conditions [10] is applied. The transverse step sizes are $\Delta x = \Delta y = \lambda/20$ and the longitudinal step size is $\Delta z = \lambda$, where $\lambda$ is the operating wavelength. The power transfer as a function of fiber length for the proposed PCF coupler is shown in figure 2. The difference between the $x$- and $y$-polarized states is found to be very low; therefore, only the curves of the $x$-polarized state are plotted.

A directional coupler can be realized by setting the fiber length to be the coupling length of the coupler, $L_c$. The coupling length of the proposed fiber is $L_c = 27$ mm. Since the first derivative of the normalized output power is zero, the deviation of fiber length from the optimal value has only a very small influence on the output power of the side cores. Therefore, the proposed fiber could have a large tolerance to the fiber length, as will be demonstrated.

Figure 3 shows the mode field transitions of the proposed coupler after a signal is launched into the center core of the coupler. At $z = 0$, we see the input field in the center core, and then the power transfers from the center core to the side cores very smoothly, and finally, at $z = L$, all power is transferred from the center core to the side cores.

To describe the characteristics of the coupler, we will first introduce the definitions of insertion loss, polarization-dependent loss (PDL), and uniformity. 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. Uniformity is defined as the difference between the highest and lowest insertion losses of the coupler output ports in the entire bandwidth range. The spectral characteristics of the fiber as a function of operating wavelength are shown in figure 4. We plotted only the insertion loss of the $x$-polarized state for simplicity. The PDL is also plotted in the figure. The available bandwidth of the coupler is defined as the wavelength range within which the insertion loss is lower than 3.4 dB, which means that over 91% of the input power can be divided into the two output ports. The bandwidth of the coupler is 425 nm, which covers the interval 1.32–1.745 $\mu$m. In addition, the PDLs are always lower than 0.06 dB in the wavelength range. Low uniformity in the entire wavelength range is another advantage of the proposed coupler. Due to the symmetry of the configuration, the power is distributed evenly between the two output ports of the coupler. This means that the uniformity of the coupler should be very low. This is in contrast to a dual-core optical fiber coupler, where the insertion losses of the two output ports are generally different. Therefore, the bandwidth of the coupler is mainly limited by the maximum insertion loss allowed.
One important issue for a PCF coupler is the tolerance of the structure parameters. Numerical investigations demonstrate that the proposed fiber is insensitive to the variation of fiber parameters. We will present here an investigation on the variation of the air-hole diameter and the fiber length on the properties of the proposed coupler.

The air-hole diameters of the coupler were enlarged or reduced by 4% to investigate their influence on the operating wavelength range of the coupler. Figure 5 shows the output power in the cores of a fiber with fiber length $L = 27$ mm and the normalized diameters of the air-holes $d/\Lambda = 0.288$ and 0.312, respectively. The reduction of the air-hole diameter leads to the movement of the available wavelength region to shorter wavelength, whereas the increase of the air-hole diameter leads to the movement of the available wavelength region to longer wavelength. The wavelength ranges where the insertion loss is lower than 3.4 dB and the PDL is lower than 0.06 dB for the fiber with $d/\Lambda = 0.288$ and 0.312, respectively. In either case, it covers the wavelength 1.55 µm. This means that the proposed fiber allows at least ±4% deviation of the air-hole diameters, that is, the air-holes should allow a tolerance of ±186 nm in diameter. It has been possible to manufacture the microstructure in an air–glass PCF to accuracies of 10 nm on the scale of 1 µm [11]. Therefore, the proposed fiber can be fabricated by present-day techniques.

The output power in the cores of a proposed fiber with fiber length $L = 24.3$ and 29.7 mm, respectively, are shown in figure 6. The available wavelength range is from 1.44 to 1.893 µm, with PDL lower than 0.08 dB and insertion loss lower than 3.4 dB for the fiber with $L = 24.3$ mm. The available wavelength range is from 1.22 to 1.622 µm, with PDL lower than 0.05 dB and insertion loss lower than 3.4 dB for the fiber with $L = 29.7$ mm. The available wavelengths cover the operating wavelength 1.55 µm in both cases. Therefore, a deviation of at least ±10% from the proposed length of 27 mm is allowed.

3. Conclusion

In conclusion, we have proposed in this paper the design of a novel PCF based directional coupler. The center-to-center distance between the two side cores is 62 µm, which implies that the output power in the two cores can be separated easily. The three-core PCF coupler opens the possibility of fabricating a novel broadband directional coupler with low PDL, uniformity, and sensitivity to the fabrication tolerance.

Acknowledgments

This work is supported by the Senior Talent Foundation of Jiangsu University, China, under project grant 06JDG062, the Natural Science Foundation of the Jiangsu Higher Education.
Institutions of China (Grant No. 08KJB510001), the National Science Foundation of China (Grant No. 10574058), Qianjiang Talent Project of Zhejiang Province (Grant No. 2007R10015), the Science Foundation of Ningbo (Grant No. 2008A610001), and the work was also supported by a grant from CityU (7001888).

References

[1] Zhang L and Yang C 2004 J. Lightwave Technol. 22 1367
[2] Chen M Y and Yu R J 2004 J. Opt. A: Pure Appl. Opt. 6 805
[3] Yue Y et al 2006 IEEE Photon. Technol. Lett. 18 2032
[4] Saitoh K, Sato Y and Koshiba M 2003 Opt. Express 11 3188–95
[5] Florous N, Saitoh K and Koshiba M 2005 Opt. Express 13 7365
[6] Chen M Y and Zhou J 2006 J. Lightwave Technol. 24 5082
[7] Sun X 2007 Opt. Lett. 32 2484
[8] Lægsgaard J, Bang O and Bjarklev A 2004 Opt. Lett. 29 2473
[9] Huang W P and Xu C L 1993 IEEE J. Quantum Electron. 29 2639
[10] Hadley G R 1992 Opt. Lett. 16 624
[11] Russell P S J 2006 J. Lightwave Technol. 24 4729