Wavelength-Selective Coupling of Dual-Core Photonic Crystal Fiber for Spatial Mode Conversion

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Abstract:- In this paper, the scheme of a wavelength-selective coupler based on dual-core photonic crystal fiber (PCF) that operates by both total internal reflection index-guided and the photonic bandgap mechanism is proposed. This contains an index-guided core and a photonic bandgap core. The first circle holes around one of the cores are filling with high-index rods. Effective mode conversions can be achieved numerically by optimizing the refractive index of these high-index rods. Also, the operating wavelength and coupling length can be continuously tuned by varying the refractive index of high-index rods. Moreover, For LP_{01}-LP_{11} mode converter has < 1dB mode-dependent loss and a coupler insertion loss <3 dB are possible, whereas for LP_{01}-LP_{21} mode converter, a mode-dependent loss <1 dB and coupler insertion loss <4 dB can be simultaneously achieved.

Key words—Mode-division multiplexing, mode converter, photonic crystal fiber.

I INTRODUCTION

Recently, space division multiplexing and mode-division multiplexing (SDM), (MDM) has attracted more and more attention in order to increase the transmission capacity [1],[2]. In MDM system, each fiber mode of the few mode fiber (FMF) will be exploited as a data channel. Hence, the key is to convert the fundamental fiber modes into higher order modes. Moreover, the mode conversion could be achieved using various bulky freespace optics [3], fiber-based mode converter promises a lower cost, more compact and more efficient mode conversion approach. Typical solutions include mode-selective coupler (MSC), and photonic lantern. Compared with photonic lantern, MSC could also take on the challenging task represented by the add-drop multiplexers for single channel [4]-[6].
Mode converters usually long-period gratings with a period matching the beat length between the modes are needed at the input and output of a higher-order mode device to couple light from and to the fundamental mode. The principle of MSC is to phase match the fundamental mode in a single-mode fiber with a high-order mode in FMF. Polished-type and fused-type MSCs had been reported so far [7], [8]. In these works, in order to meet the phase-matching condition, one of the fibers should be tapered to control the radius of fiber core before fused and polished. During the fabrication process, it must be careful to keep the core shape and avoid fragmentation Anticipating these problems, MSC based on single multicore fiber (MCF) is a good option [9].Compared with conventional MCF, multicore photonic crystal fiber (PCF) possesses more flexible waveguide structures and coupling characteristics, for example, the light-guiding mechanism of different cores in a single multicore PCF can be different [10].

In this paper, a wavelength-selective mode converter is proposed based on a dual-core air-hole PCF. An index-guided core and a photonic bandgap (PBG) core which characterizes PBG light guiding mechanism are contained in this fiber. The first circle holes around PBG core are replaced with high-index rods. Phase-matching condition is satisfied by optimizing the refractive index of these high-index rods. Numerical methods are employed to analyze the coupling characteristics of this structure. Simulated results show that efficient mode conversions can be realized between fundamental mode (LP01) and high-order modes (LP11, LP21). Another interesting result is that the bandwidth of this mode converter could vary from ten to dozens of nanometers. For our design, it could be fabricated using PCF post-processing of selective filling of air-holes with an index tunable material or PCF fabrication technique. In addition, the converter is insensitive to polarization by choosing appropriate hole pitch and hole diameter.

II WAVELENGTH-SELECTIVE MODE CONVERSION BASED ON DUAL-CORE PHOTONIC CRYSTAL FIBER

A. *Schematic of Dual-Core Photonic Crystal Fiber*

Our proposal is based on a wavelength selective dual-core PCF structure displayed in Fig. 1. The understructure of this dual-core PCF is an air-hole PCF whose hole pitch (Λ) = 5 μm and hole diameter d = 2 μm. Background silica index is assumed to be 1.45. Different from the conventional dual-core PCF, this structure shares properties of both the total internal reflection (TIR) index-guided and the photonic bandgap (PBG) mechanism. As it is shown in Fig. 1, the right core is an index-guided core which guides light by modified total internal reflection mechanism. Its diameter is about 20 μm supporting four modes (LP01, LP11, LP21 and LP02) by removing the central air hole and first circle air holes. The right core is PBG core which guides light by photonic bandgap mechanism (PBG). The first circle holes around it are replaced with high-index rods or index tunable rods (n = $n1$), so it characterizes photonic bandgap light guiding mechanism in which guide modes exist only in restricted bands of wavelength. Inter-modally phase-matching condition between two cores could be satisfied by optimizing refractive index of high-index rods $n1$.

The hole in the middle of two cores in a dual-core PCF is designed for special mode conversion purpose. The size, position and index of this hole will influence the coupling coefficient between the modes, as well as its confinement in the core. It is also important to calculate the possible coupling efficiency. We denote the refractive index of material filled in this hole by $n3$.

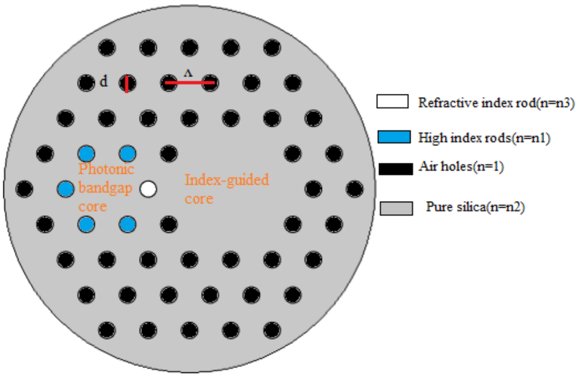
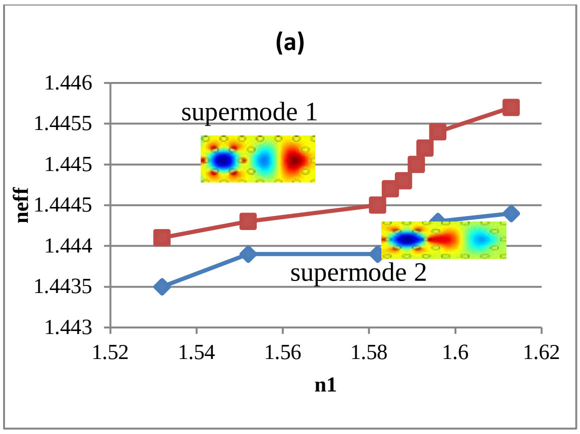


Fig.1. Schematic of dual-core photonic crystal fiber.



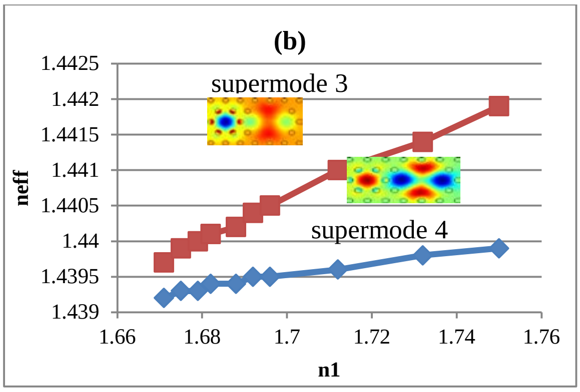


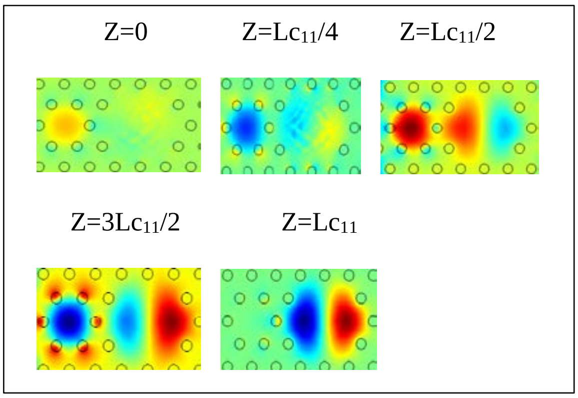
Fig. 2 (a), (b) There are supermode 1, 2 in the region between n = 1.532 and n = 1.623, and supermode 3, 4 between n = 1.652 and n = 1.732 at the operating wavelength 1.55μm. The effective index of supermode 1-4 varies according to the change of index $n1$ (assume $n3$ = $n1$).

B. Numerical Analysis and Simulated Results

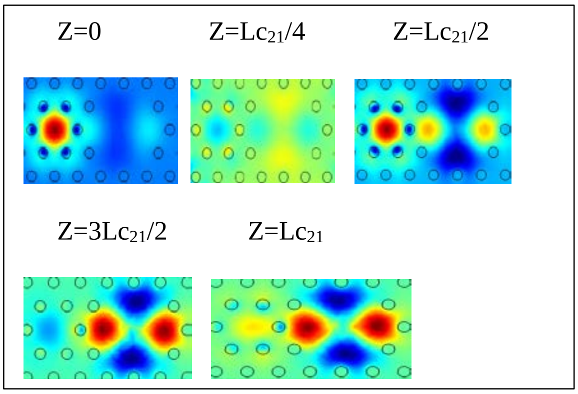
Next, the supermodes in the two coupled cores as one photonic crystal fiber (PCF) are investigated. Assuming $n3$ = $n1$. The operating wavelength is 1.55 μm. In order to find the optimal values of $n1$ which could satisfy the condition of mode conversion, we scan the value of $n1$ and get the pattern and effective index of supermodes. Figure 2 shows the effective index curves of four concerned supermodes. We call supermode 1, 3 symmetric mode and call supermode 2, 4 antisymmetric mode to distinguish them. The effective index of symmetric mode is always slightly larger than that of antisymmetric mode. If you excite both the symmetric and the antisymmetric mode, that have different propagation constants, there is a beating between these two waves. Thus, you see that the power fluctuates back and forth between the two cores. It has a coupling length Lc defined by

$$L_C = \frac{2\pi}{\beta s - \beta as}$$

Where βs and βas represent the propagation constant of symmetric and antisymmetric mode.



(a)



(b)

Fig. 3 (a), Mode field distributions along the propagation direction at Z = 0, $Lc11/4$, $Lc11/2$, $3Lc11/4$ and $Lc11$, respectively.3 (b) Mode field distributions at Z = 0, $Lc21/4$, $Lc21/2$, $3Lc21/4$ and $Lc21$, respectively. Operating wavelength (λn) is 1.55 μm.

The overall coupler insertion loss (CIL) can therefore be evaluated as,

$$\text{CIL} = \left(\frac{1}{N}\sum_{n=1}^{N}\lambda_n^{2}\right)^{-1}$$

And the mode-dependent loss (MDL) defined as the ratio between the strongest and the weakest intensity transfer coefficient is given by

$$\text{MDL} = Max(\lambda)_n^2/Min(\lambda)_n^2$$

λn represent the intensity transmission coefficient of the *N* orthogonal coupled channels.CIL and MDL are the characteristics of interest to evaluate the performance of a mode coupler. Low CIL is desirable in particular for the receiving mode multiplexer, in order to avoid degradation of the optical signal-to-noise ratio due to added loss. Small MDL is desirable to avoid capacity loss and minimize outage probability [7] of the transmission link. In coupled mode theory, each core is treated as an independent waveguide that is perturbed by the presence of fields propagating in the other core. Since the supermodes can be built up from the modes of each core in isolation, we calculated the effective index of a single index-guided core PCF and that of photonic bandgap core PBGF. Generally, the intensity distribution of symmetric mode is similar to that of antisymmetric mode when the power could fluctuates back and forth between the two cores efficiently, thus the effective mode index of symmetric mode is just slightly larger than that of antisymmetric mode. From Fig. 2(a), 2 (b) we know that efficient mode conversions may occur in the vicinity of $n1$ = 1.532 and $n1$ = 1.623 for LP_{01}-LP_{11} and n1=1.652 and n1=1.732 for LP_{01}-LP_{21}. Combined with the beam propagation method (BPM), we can find the optimal values of $n1$. Figure 3(a) shows the process of mode conversion between LP01 mode and LP11 mode along the propagation direction Z when $n1$ = 1.562 using BPM. The coupling efficiency is 96% with the beat length $Lc11 = 4.27\ mm$. Figure 3(b) shows the process of mode conversion between LP01 mode and LP21 mode when $n1$ = 1.676. The coupling efficiency is 91% with the beat length $Lc21 = 4.7\ mm$.

Taking into account the actual fabrication process, it would be useful to consider how the coupling efficiency varies according to the change of proposed refractive index. According to the results discussed above, we know that in order to achieve efficient mode conversion, a particular value of index $n1$ is needed. If this value is not accurate, it will reduce the coupling efficiency.

III. PERFORMANCE DISCUSSION

In the previous section, efficient mode conversions have been realized at the particular free space wavelength $\lambda = 1.55\ \mu m$ by choosing appropriate index $n1$. In fact, operating wavelength of these two mode couplers is adjustable because the phase matching wavelength varies with the change of index $n1$. When $n1$ is increased, the operating wavelength also increases in fig.4 (a), 4(b).

Results calculated under the assumption of single core fiber work well for LP01-LP11 coupler. When $n1$ is increased, the coupling length will also change. Figure 5(a), 5(b) shows that the coupling length is inversely proportional to index $n1$. . Mode-dependent loss (MDL) and overall coupler insertion loss (CIL) is another important property for optical devices.

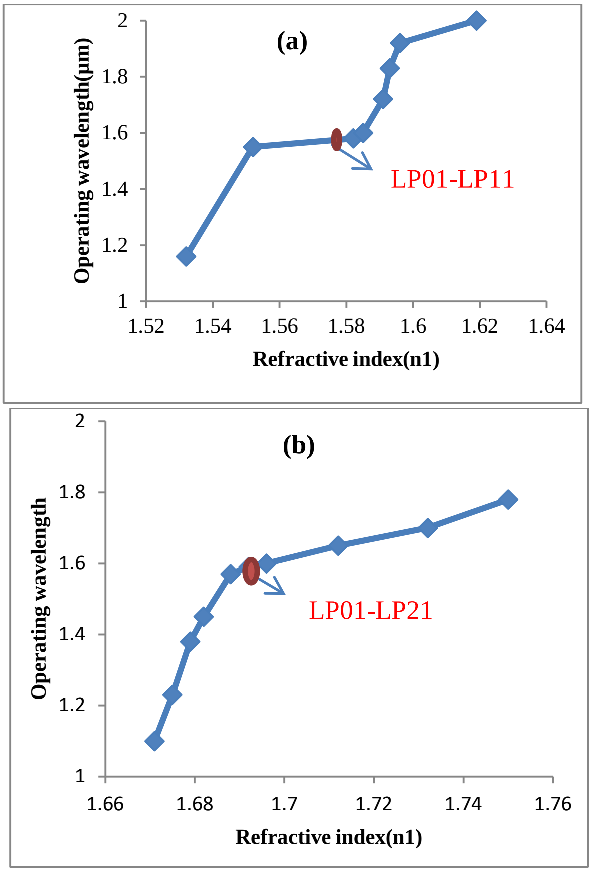


Fig. 4 (a), 4 (b) Operating wavelength increases with the growth of index $n1$.

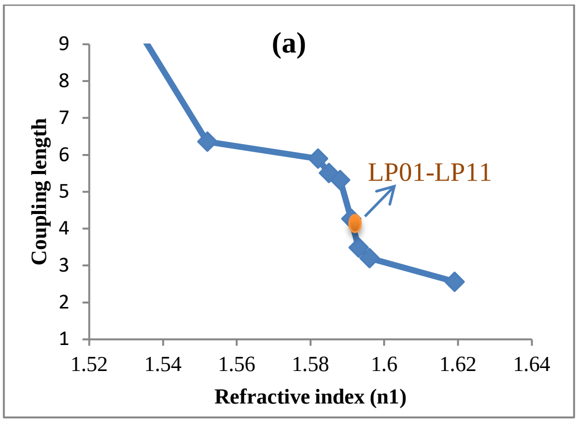


Fig. 5(a) The coupling length decreases with the growth of index $n1$ for LP_{01}-LP_{11}.

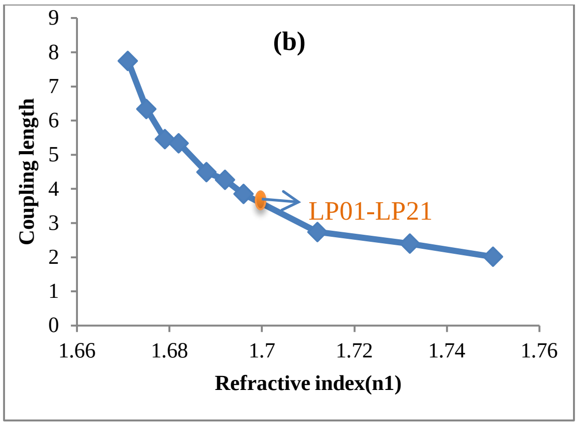


Fig. 5(b) The coupling length decreases with the growth of index $n1$ for LP_{01}-LP_{21}.

The size, position and index of the hole in the middle of two cores have a profound impact on the coupling coefficient between the modes. The MDL and CIL of mode coupler varies with the change of operating wavelength (λn). A mode-dependent loss and coupling insertion loss of LP01-LP11and LP01-LP21 mode coupler is 0.42 dB and 7.6 dB and 0.31dB and 6.2 dB respectively. And also, the mode coupler is insensitive to polarization. Because the difference in effective index of the orthogonal polarizations for each mode is less than 1.0E-4 by choosing hole pitch = 5 μm and hole diameter d = 2 μm [10].

CONCLUSION

In conclusion, spatial mode conversion based on wavelength-selective coupling of dual-core photonic crystal fiber has proposed. This shares the properties of both total internal reflections (TIR) index-guided and photonic bandgap mechanisms. By filling of index n1 and n3, the mode conversion between LP01 and LP11 and between LP01 and LP21 mode achieved respectively. Moreover, the operating wavelength and coupling length continuously tuned by changing the refractive index of high index rods. A mode-dependent loss of those mode converters is <1dB with low insertion loss.

REFERENCE

[1] X. Sun, "Wavelength-selective coupling of dual-core photonic crystal fiber with a hybrid light-guiding mechanism," *Opt. Lett.*, vol. 32, no. 17, pp. 2484–2486, 2007.
[2] K. Lai, S. G. Leon-Saval, A. Witkowska, W. J. Wadsworth, and T. A. Birks, "Wavelength-independent all-fiber mode converters," *Opt.Lett.*, vol. 32, no. 4, pp. 328–330, 2007.
[3] S. G. Leon-Saval, A. Argyros, and J. Bland-Hawthorn, "Photonic lanterns: A study of light propagation in multimode to single-mode converters," *Opt. Exp.*, vol. 18, no. 8, pp. 8430–8439, 2010.
[4] R.Ryf, N. K .Fontaine, and R. J. Essiambre, "Spot-based mode couplers for mode-multiplexed transmission in few-mode fiber," *IEEE Photon. Technol. Lett.*, vol. 24, no. 21, pp. 1973–1976, Nov. 1, 2012.
[5] D. Richardson, J. Fini, and L. Nelson, "Space-division multiplexing in optical fibres," *Nature Photon.*, vol. 7, no. 5, pp. 354–362, 2013.
[6] N. Riesen and J. D. Love, "Ultra-broadband tapered mode-selective couplers for few-mode optical fiber networks," *IEEE Photon. Technol. Lett.*, vol. 25, no. 24, pp. 2501–2504, Dec. 15, 2013.
[7] T. Watanabe and Y. Kokubun, "Ultra-large number of transmission channels in space division multiplexing using few-mode multi-core fiber with optimized air-hole-assisted double-cladding structure," *Opt. Exp.*, vol. 22, no. 7, pp. 8309–8319, 2014.
[8] R. Ismaeel, T. Lee, B. Oduro, Y. Jung, and G. Brambilla, "All-fiber fused directional coupler for highly efficient spatial mode conversion," *Opt. Exp.*, vol. 22, no. 10, pp. 11610–11619, 2014.
[9] S. Yerolatsitis, I. Gris-Sánchez, and T. A. Birks, "Adiabatically-tapered fiber mode multiplexers," *Opt. Exp.*, vol. 22, no. 1, pp. 608–617, 2014.
[10] S. Cai, S. Yu, M. Lan, L. Gao, S. Nie, and W. Gu, "Broadband mode converter based on photonic crystal fiber," *IEEE Photon. Technol. Lett.*, vol. 27, no. 5, pp. 474–477, Mar. 1, 2015.
[11] S. Cai, S. Yu, Y.Wang, M Lan, Li Gao, and Wanyi Gu," Hybrid Dual-Core Photonic Crystal Fiber for Spatial Mode Conversion", *IEEE Photon. Technol. Lett*, vol. 28, no. 3, Feb 1, 2016.