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MODE COUPLING IN THREE-CORE PHOTONIC CRYSTAL FIBER FOR SPATIAL MODE CONVERSION

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Abstract— *In this paper, the scheme of mode conversion based on mode coupling in a three-core photonic crystal fiber is proposed. This contains an index-guided core and two photonic band gap cores. The high-index rods replace a first circle of air holes around one of the PCF cores. Efficient mode conversions can be achieved numerically by optimizing the refractive index of these high-index rods. Moreover, the coupling length and the operating wavelength can be continuously tuned by changing the refractive index of the high-index material. In addition, the mode converter is insensitive polarization.*

Key words: *Photonic crystal fiber, Mode-division multiplexing, Mode converter*.

I. INTRODUCTION

Recently, mode-division multiplexing (MDM) has attracted more and more attention in order to increase the transmission capacity [1]–[2]. In MDM system of each fiber mode of the few mode fiber (FMF) will be exploited as a data channel. Hence, the key is to convert the fundamental modes into higher order modes [3]. Although mode conversion could be achieved by various bulky free space Optics [5], fiber-based mode converters promises a lower cost, more efficient mode conversion and more compact [6]–[7]. The principle of MSC is to phase match the fundamental mode in a single-mode fiber with a high-order mode in FMF[8] Compared with conventional MCF, multicore photonic crystal fiber (PCF) possesses coupling characteristics and more flexible waveguide structures, for example, the light-guiding mechanism of different cores in a single multicore PCF can be different [9]. Over twenty years ago, such mode selective couplers (MSCs) had been introduced as an essential building block for a number of multimode fiber devices such as sensors, accelerometers, strain gauges, amplitude modulators, frequency shifters, and chromatic dispersion compensators [10]. The principle of the coupler is to phase match the fundamental mode in one fiber with a high-order mode in a few-mode fiber (FMF) and so achieve conversion to the higher- order mode. Several techniques were suggested and implemented to achieve this mode conversion, including polished couplers , stress induced modal couplers [11] and fused etched multi-mode couplers [12],[14].

In this letter, an efficient mode converter is proposed based on a three-core air-hole PCF. An index guided core and a photonic band gap (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. Phase-matching condition is satisfied by optimizing the index of these high-index rods. 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 is calculated.

For our design, it could be fabricated using PCF post processing of selective filling of air-holes with an index tunable material. In addition, the converter is insensitive to polarization by choosing appropriate hole pitch and hole diameter.

II. MODE CONVERSION BASED ON THREE-CORE PHOTONIC CRYSTAL FIBER

A. Schematic of Three-Core Photonic Crystal Fiber

Our proposal is based on a three-core PCF structure displayed in Fig. 1. The understructure of this three core PCF is an air-hole PCF whose hole pitch = 5 μm and hole diameter d = 2 μm. Background silica index is assumed to be 1.45. Different from the conventional three-core PCF, these structure shares properties of both the total internal reflection (TIR) index-guided and the photonic band gap mechanism. As it is shown in Fig. 1, the center core is index guided core which guides light by modified total internal reflection mechanism and the both ends of the core as photonic band gap core which guides light by photonic band gap mechanism. Its diameter is about 20 μm supporting four modes (LP01, LP11, LP21 and LP02) by removing the central and first circle air holes. The first circle holes around it are replaced with high-index 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 index $n1$.

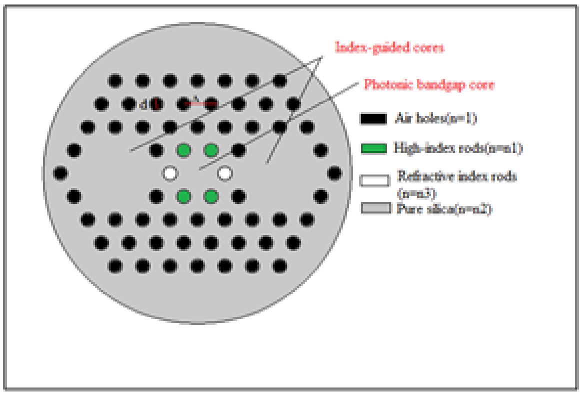
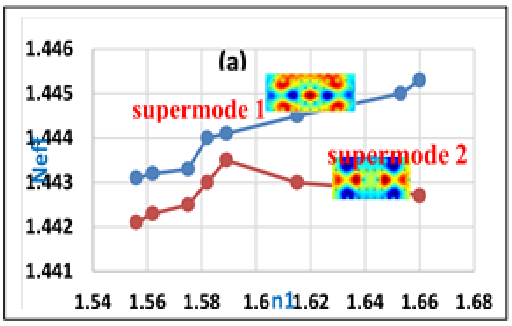


Fig.1. Schematic of three-core photonic crystal fiber.



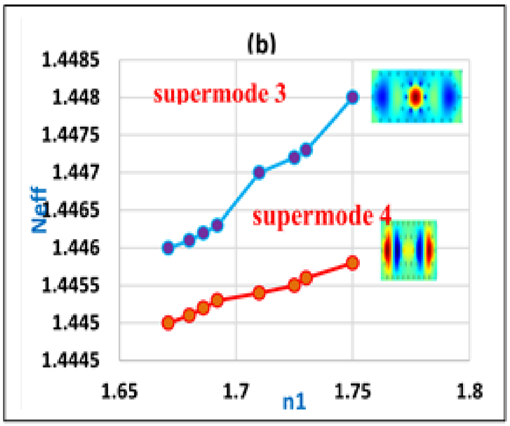


Fig.2 (a).There are supermode 1, 2 in the region between n = 1.542 and n = 1.65. (b).There are supermode 3, 4 in the region between n = 1.67 and n = 1.75 at the operating wavelength 1.55μm. The effective index of supermode 1-4 varies according to the change of index $n1$ (assume $n3$=$n1$).

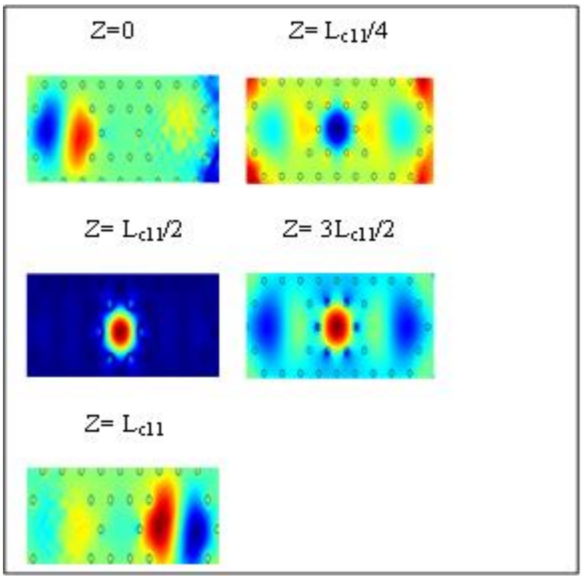
The hole in the middle of three cores in a three-core PCF is designed for special purpose. The size, position and index of this hole will influence the coupling coefficient between the modes, as well as its confinement in the core. It is also important to calculate the possible coupling efficiency. We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

B. Numerical Analysis and Simulated Results

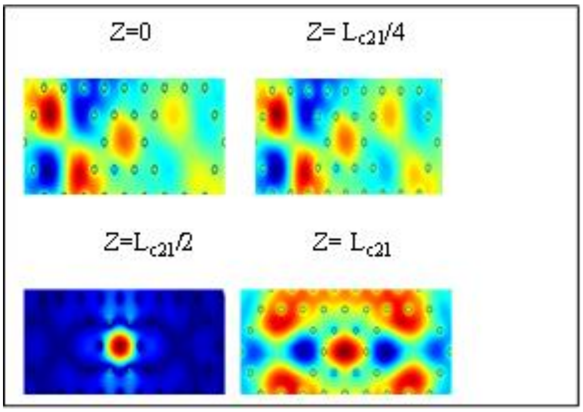
Next, the supermodes in the two coupled cores as one PCF are investigated. Assuming $n3$ = $n1$. The operating wavelength is 1.55 μm. In order to find the optimal values of $n1$ which could satisfy the condition of mode conversion, we scan the value of $n1$ and get the pattern and effective index of supermodes. Figure 2 shows the effective index curves of four concerned supermodes. We call supermode 1, 3 as a symmetricmode and call supermode 2, 4 as antisymmetricmode to distinguish them. The effective index of symmetric mode is always slightly larger than that of antisymmetric mode. The mismatch between the three cores is usually sufficiently large and their propagation constants are not matched, light propagates independently in each core, and no power transfer occurs. However, the high refractive index can be chosen to impose phase matching between the two adjacent cores at a particular wavelength (λ), at which the propagation constants of the two cores are equal and $\beta_{TIR}(\lambda)=\beta_{PBG}(\lambda)$. The coupling happens only over a very small wavelength range. 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 beat length L_c defined by

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

Where β_s and β_{as} represent the propagation constant of symmetric and antisymmetric mode. The propagation constant β for the eigenmodes can be obtained from $\beta = n_{eff}k$, where $k=2\pi/\lambda$ is the wave vector and λ is the wavelength in vacuum.



(a)



(b)

Fig.3 (a) Mode field distribution along the direction at Z=0, Lc11/4, Lc11/2, 3Lc11/2 and Lc11 respectively. (b) Mode field distribution along the direction at Z=0, Lc21/4, Lc21/2 and Lc21 when operating wavelength (λ) is 1.55µm.

Generally, the intensity distribution of symmetric mode is similar to that of antisymmetric mode when the power could fluctuates back and forth between the three cores efficiently, thus the effective index of symmetric mode is just slightly larger than that of antisymmetric mode. From Fig. 2(a) and (b) we know that efficient mode conversions may occur in the vicinity of $n1 = 1.568$ and $n1 = 1.75$. 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 $n1 = 1.732$ using BPM. The coupling efficiency is 97% with the beat length $Lc11 = 5.45$ *mm*. Figure 3(b) shows the process of mode conversion between LP01 mode and LP21 mode when $n1 = 1.568$. The coupling efficiency is 91% with the beat length $Lc21 = 4.25$ *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 (Fig. 4(a)). Fig. 4(a) that wavelength $1.55\mu m$ corresponding to crossing point for LP01-LP11 mode coupler is in good agreement with the exact value obtained using supermode analysis. When $n1$ is increased, the coupling length will also change. Figure 6(a) and (b) shows that the coupling length is inversely proportional to index $n1$.
Wavelength bandwidth is another important property for optical devices. We are interested in the bandwidth of our mode couplers. 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.

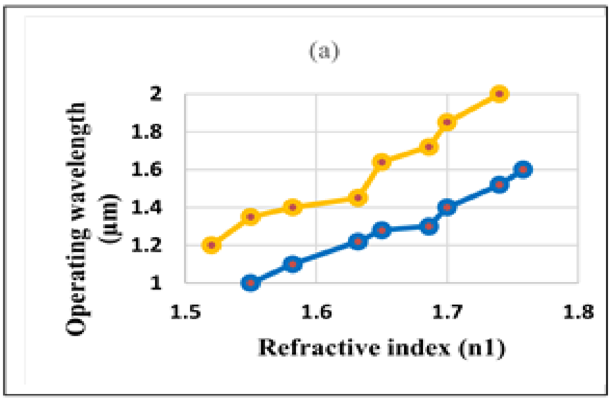


Fig. 5(a) Operating wavelength increases with the growth of index *n*1.

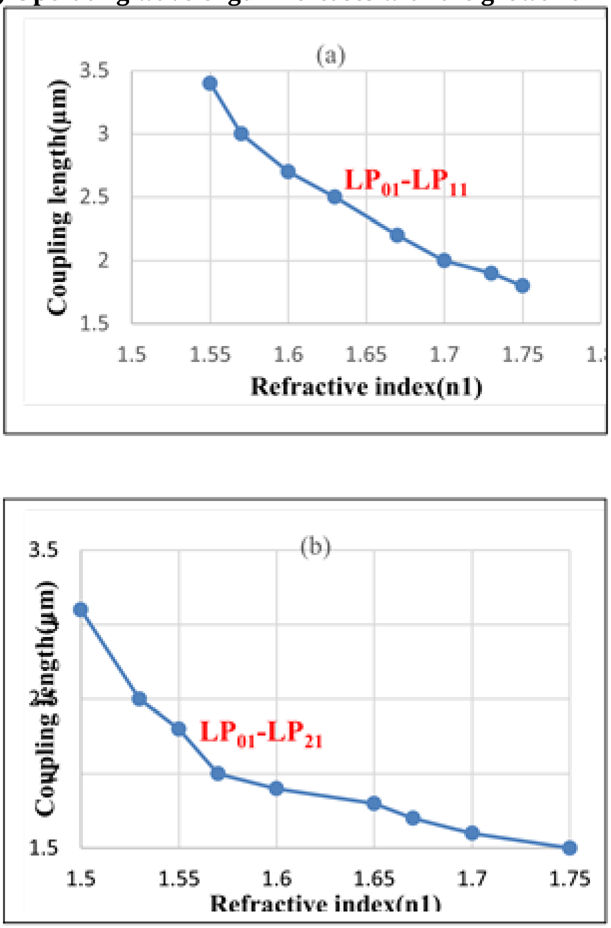
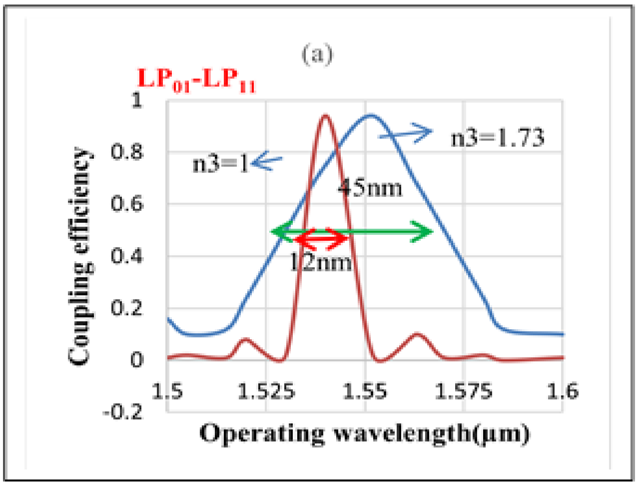


Fig. 6(a), (b) The coupling length decreases with the growth of index $n1$.



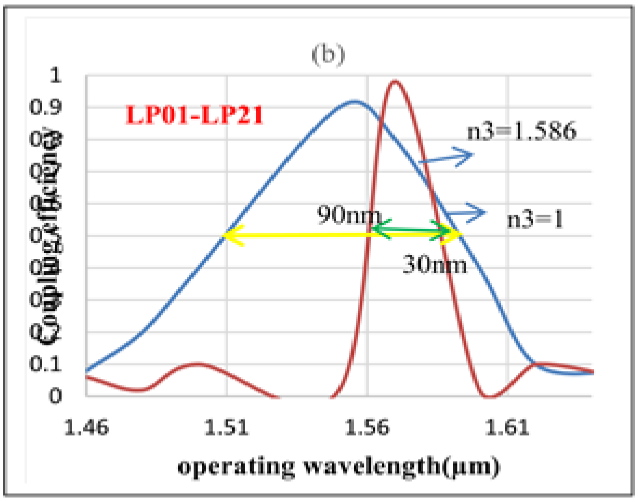


Fig.7. Bandwidth of (a) LP01-LP11 mode coupler and (b) LP01-LP21 mode coupler. Blue and red solid lines represent the coupling efficiency in the position of operating beat length when $n3 = n1$, $n3 = 1$ respectively.

Figure 7(a) shows that the bandwidth of LP01-LP11 mode coupler varies with the change of hole index $n3$. It can be observed that the minimum bandwidth corresponds to $n3 = 1$ (12 nm) and the maximum bandwidth corresponds to $n3 = n1$ (45 nm). Note that the minimum value of bandwidth can be as low as 10 nm which has the potential to be used as a wavelength selective coupler. The performances of LP01-LP21 mode coupler are illustrated in Fig. 6(a), (b). We can see the maximum bandwidth value can reach 90 nm. In order to make the wavelength bandwidth of these two mode couplers broader, we could choose the case of $n3 = n1$. Moreover, 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 $d = 2\ \mu m$ [14].

IV CONCLUSION

In conclusion, we made fiber mode converter based on mode coupling in a three core photonic crystal fiber. This can be fabricated by PCF post processing of selective filling of air-holes with a refractive index tunable material. Different from traditional PCFs, this structure shares properties of both the TIR index-guided and PBG mechanism. After choosing the refractive index $n1$ and $n3$, mode conversions between LP01 and LP11 and between LP01 and LP21 mode are achieved efficiently and also the bandwidth of mode converter is calculated that depends on the index n1. The operating wavelength and the coupling length can be continuously tuned by changing the refractive index of the high-index material. In addition, the mode converter is insensitive polarization.

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