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Abstract. A single-polarization single-mode (SPSM) photonic crystal fiber (PCF) coupler is designed and investigated by using full-vector finite-element method with the anisotropic perfectly matched layer. We numerically analyze the SPSM coupling properties with respect to the structure parameters and confinement loss characteristics. The results reveal that the coupling length between dual cores is as small as millimeter order of magnitude due to the wide silica bridge of energy transfer, and the SPSM coupling region can be tailored to cover the communication windows of 1.3 or 1.55 μm with optimized design parameters. Moreover, the confinement loss of x polarization is 3 orders of magnitude larger than that of y polarization in single polarization range. The proposed SPSM PCF coupler may find application in polarization-sensitive systems. © The Authors. Published by SPIE under a Creative Commons Attribution 3.0 Unported License. Distribution or reproduction of this work in whole or in part requires full attribution of the original publication, including its DOI. [DOI: 10.1117/1.OE.55.2.027101]

Keywords: coupler; single polarization; photonic crystal fiber; confinement loss; coupling length.

Paper 151630 received Nov. 19, 2015; accepted for publication Jan. 11, 2016; published online Feb. 2, 2016.

1 Introduction

Photonic crystal fibers (PCFs), also known as microstructured optical fibers, have attracted considerable research interest due to their unique photonic controlled advantages, and kinds of PCFs with special characteristics were successively put forward to meet various demands.^{1–5} The flexible control of air hole allows the construction of complex dual-core or multicore structures.^{6,7} Couplers, which can guide light power to other optical components in appropriate proportions, are essential for all-fiber systems and have been extensively applied in optical fiber sensing systems and coherent optical communication systems.^{8,9} For conventional optical fiber couplers, the coupling intensity between the propagation modes of two cores is weak due to long separated distance, which leads to long length of couplers.¹⁰

In recent years, couplers based on PCFs have attracted people's attention since the PCF coupler was experimentally investigated by Mangan et al.¹¹ Compared with conventional couplers, very short coupling length and other new features can be realized by changing the structural dimensions of PCF couplers. Furthermore, optical passive components based on PCF couplers, such as polarization splitters^{12,13} and wavelength splitters,¹⁴ were also designed and investigated. However, for common PCFs or PCF couplers, the inherent polarization mode coupling and polarization mode dispersion will deteriorate the performance of systems in certain polarization-sensitive applications like fiber optic gyroscopes and high-power fiber lasers.^{1,14} The ability of suppressing one polarization fundamental mode in single-polarization single-mode (SPSM) PCFs or PCF couplers makes them good candidates for polarization-sensitive occasions. In our previous work, the investigation of SPSM PCFs has been carried out¹⁵ and therefore, this paper focuses on the SPSM PCF coupler.

The SPSM PCF coupler was first proposed by Yue et al.,¹⁶ in which the SPSM coupling range was more than 200 nm and the SPSM coupling region could be tuned by varying the size of the surrounding air holes of the dual cores. Then, Li et al.¹⁷ designed a double-core SPSM coupler whose coupling lengths were of millimeter order of magnitude, and the SPSM coupling operation could be realized within a wide wavelength range. The rectangular-lattice SPSM coupler was investigated by Liu and Li,¹⁸ and the wide SPSM coupling range could be also realized. Afterward, on the basis of the dual-core PCF coupler, the SPSM wavelength splitter was proposed by Zhang et al.¹⁴ and calculated results showed that the wavelength splitter could split two different wavelengths between 1.3 and 1.55 μm at a fiber length of 10.7 mm with the single polarization guiding.

In this paper, a novel SPSM PCF coupler with the triangular lattice is proposed. The full vector FEM is applied to investigate the coupler's properties, including power distributions of four supermodes, SPSM coupling characteristics, and confinement losses of two polarization modes. The calculated results show that the proposed PCF coupler can realize SPSM coupling operation within a wide wavelength range, and the SPSM coupling region can be tuned by adjusting the structure parameters. Due to the wide silica bridge of energy transfer between dual cores in the proposed structure, the coupling length is as small as millimeter order of magnitude. The separated distance between two cores is larger than that of other PCF couplers,^{16–18} which may make it convenient to connect with other output devices. In addition, the x polarization modes have 3 orders of magnitude larger confinement loss than y polarization modes in single-polarization coupling range.

2 Structure Design and Theory

The transverse structure of the proposed SPSM PCF coupler is shown in Fig. 1, where Λ denotes the hole pitch (center-to-center distance between the proximal holes), d and D are the

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Fig. 1 Transverse structure of the proposed SPSM PCF coupler.

diameters of small holes and enlarged holes, respectively. The number of rings of arrays of air holes is represented by the symbol N_r that is assumed to be 6 in the following calculation. In order to realize the single polarization operation, two enlarged air holes are placed around each core. The separated distance between dual cores is equal to $2\sqrt{3}\Lambda$, which may make it convenient to splice with output devices. When we establish the model of the proposed PCF coupler, the refractive index of air holes is assumed to be 1.0 and the background silica index can be obtained by Sellmeier formula.¹⁹

Because of the twofold symmetry for the proposed PCF coupler, x polarization and y polarization modes are no longer degenerate. According to the coupled-mode theory, four nondegenerate fundamental modes (supermodes) exist in the proposed coupler, namely, odd modes in x polarization and y polarization and even modes in x polarization and y polarization. When the light power propagates along the fiber, the odd mode and even mode in the same polarization can couple with each other. Coupling length for x or y polarization modes, determined by the effective refractive index difference between even and odd modes, can be obtained by^{20,21}

$$L_i = \frac{\pi}{|\beta_{\text{even}}^i - \beta_{\text{odd}}^i|} = \frac{\lambda}{2|n_{\text{even}}^i - n_{\text{odd}}^i|}, \quad (1)$$

where $i = x, y$, β_{even}^i and β_{odd}^i denote the propagation constants of even modes and odd modes for the i polarization, n_{even}^i and n_{odd}^i are the corresponding effective refractive indexes, respectively.

Assuming that the light is launched into core A shown in Fig. 1, the power will transform to the other core and back again when the light propagates along the PCF coupler. At a certain propagation distance, the light powers in cores A and core B can be given by¹⁷

$$P_{\text{out}}^A = P_{\text{in}} \cos^2(C_i L), \quad (2)$$

$$P_{\text{out}}^B = P_{\text{in}} \sin^2(C_i L), \quad (3)$$

where P_{in} is the power of the launched light, L is the propagation distance in the PCF coupler, and C_i denotes the coupling coefficient for the corresponding i polarization, respectively, which can be calculated by

$$C_i = k_0(n_{\text{even}}^i - n_{\text{odd}}^i)/2. \quad (4)$$

Due to a finite number of rings of air holes in the coupler, partial mode field power will leak out to the cladding. In order to accurately evaluate the confinement loss, an anisotropic perfectly matched layer (PML)^{22,23} is adopted as the absorbing boundary condition during the calculation. When the complex values of effective indexes are calculated out, the confinement loss can be obtained by

$$L_C = -\frac{40\pi}{(\ln 10)\lambda} \text{Im}(n_{\text{eff}}) = -8.686 \text{Im}(k_0 n_{\text{eff}}), \quad (5)$$

where $\text{Im}(n_{\text{eff}})$ denotes the imaginary part of the complex effective index.

3 Numerical Simulation

To investigate the properties of the proposed PCF coupler, we apply a full vector modal solver based on FEM with curvilinear hybrid edge/node elements that can model curved boundaries with more accuracy.^{24–26} As one widely used method to model PCFs, the FEM is capable of flexibly and accurately dealing with the complicated structure with arbitrary-shape air holes.^{27,28}

3.1 Power Distribution and Cutoff Characteristics

We first investigate the mode field distributions of even and odd modes for the PCF coupler with $\Lambda = 2.2 \mu\text{m}$, $d/\Lambda = 0.4$, and $D/\Lambda = 0.95$. The field distributions of four supermodes for x and y polarizations at the wavelength of $1.0 \mu\text{m}$ are shown in Fig. 2, where Figs. 2(a) and 2(b) are the even mode and odd mode in y polarization, and Figs. 2(c) and 2(d) are the even mode and odd mode in x polarization, respectively. The arrows in Fig. 2 represent the directions of the electric field vector. It can be clearly seen in Fig. 2 that four fundamental modes are well confined in the dual-core region, and the electric field directions in dual-cores are identical for even modes but opposite for odd modes.

The cutoff property of even and odd modes for the PCF coupler is analyzed in detail. Figure 3 shows the effective refractive indexes of four supermodes and cladding as a function of wavelength with $\Lambda = 2.2 \mu\text{m}$, $d/\Lambda = 0.4$, and $D/\Lambda = 0.95$. The cladding effective index is assumed to be the index of fundamental space-filling mode that can be obtained by applying FEM to an elementary piece of the cladding.^{14,15} It is well known that only the mode whose effective index is larger than that of the cladding can be guided in the core, and therefore, the cutoff of each supermode takes place at the intersection points between the cladding index line and the corresponding supermode index line. We can see in Fig. 3 that the effective indexes of the y polarization are higher than that of the x polarization,

Fig. 2 Mode field distributions of (a) even mode and (b) odd mode in y polarization and (c) even mode and (d) odd mode in x polarization at the wavelength of $1.0 \mu\text{m}$. The structure parameters are set as $\Lambda = 2.2 \mu\text{m}$, $d/\Lambda = 0.4$, and $D/\Lambda = 0.95$.

and the even mode has a higher effective index than the odd mode in x or y polarization. As a result, the cutoff wavelengths of the y polarization modes are longer than that of the x polarization modes, and in the same polarization, the cutoff of the odd mode takes place at a shorter wavelength while the even mode at a longer wavelength. Special attention should be given to the fact that both the odd and even modes should be located in the guiding region (above the cladding line) to ensure effective coupling.¹⁶ Finally, we can acquire the SPSM coupling region ranging from the intersection points 1 to 2, where the points 1 is the cutoff wavelength of the even mode of x polarization and point 2 corresponds to that of the odd mode of y polarization. In the SPSM coupling region, both the odd and even modes of the y polarization can be guided while x polarization modes are completely eliminated.

Here, the cutoff wavelength of the even mode of x polarization (point 1) is about $1.378 \mu\text{m}$ and that of the odd mode

Fig. 3 Effective refractive indexes as a function of wavelength for the proposed coupler with $\Lambda = 2.2 \mu\text{m}$, $d/\Lambda = 0.4$, and $D/\Lambda = 0.95$.

of y polarization (point 2) is about $1.597 \mu\text{m}$. Therefore, the SPSM coupling range is $\sim 219 \text{ nm}$. In addition, n_{odd}^y and n_{even}^y of odd and even modes for y polarization at the wavelength of $1.55 \mu\text{m}$ are calculated to be about 1.417978 and 1.417513. According to Eq. (1), the coupling length can be worked out about 1.67 mm. Then, we can put it into Eqs. (2) and (3) and obtain the powers at a propagation distance in dual cores.

3.2 Single-Polarization Single-Mode and Coupling Characteristics

The variation of structural parameters can lead to the changes of the SPSM coupling region and coupling lengths. Therefore, it is necessary to investigate the variation tendency with different values of the structure parameters. We first analyze the impact of changing the size of the parameter D/Λ on the SPSM coupling region. Figure 4 shows the dependent relationship between wavelengths and effective indexes of the cladding and supermodes with different values of D/Λ . When D/Λ varies to be 0.93 and 0.97 (0.95 shown in Fig. 3), the structural parameters Λ and d/Λ are fixed to be $2.2 \mu\text{m}$ and 0.4. It can be clearly seen in Figs. 3 and 4 that with the increase of the diameter D , the cutoff wavelengths of supermodes shift toward the short wavelength direction, and meanwhile, the SPSM coupling range slightly increases. Then, the impact of changing the parameter D/Λ on the coupling length within the SPSM coupling region is investigated, as shown in Fig. 5. We can see that for a fixed value of D/Λ , the coupling length decreases with the increase of wavelength, which can be attributed to the fact that the field areas of supermodes increase with increasing wavelength, thus quickening the power transfer between dual cores. Moreover, it is notable that the coupling length is shorter than that in Refs. 14 and 17, though the separated distance between two cores increases. The reason for this is that the coupling intensity not only depends on the separated distance of cores but also the silica bridges of energy transfer. In the proposed PCF coupler, the wider silica bridge of energy transfer enhances the coupling intensity and offsets the decrease due to larger separated distance between two cores.

Fig. 4 Effective refractive indexes as a function of wavelength for the proposed coupler with different values of D/Λ : (a) 0.93 and (b) 0.97. The values of Λ and d/Λ are fixed to be $2.2 \mu\text{m}$ and 0.4.

Fig. 6 Effective refractive indexes as a function of wavelength for the proposed coupler with different values of d/Λ : (a) 0.38 and (b) 0.42. The values of Λ and D/Λ are fixed to be $2.2 \mu\text{m}$ and 0.95.

Fig. 5 The dependence of coupling length on wavelength under different values of D/Λ .

Furthermore, the influences of variation of the parameter d/Λ on the SPSM coupling region are also investigated. Figure 6 shows the dependence of effective indexes of the cladding and supermodes on wavelengths for different d/Λ , whose value is set to be 0.38 and 0.42 (0.40 shown in Fig. 3). It can be found that with the increase of d/Λ , the SPSM coupling region apparently moves to the long wavelength direction, which is mainly ascribed to the fact that increasing the value of d/Λ makes the air filling fraction larger and thus the effective index of the cladding decreases. Figure 7 shows the coupling length as a function of wavelength in SPSM coupling region with different values of d/Λ . When the air filling fraction becomes larger, the silica bridge of energy transfer between dual cores becomes more narrowed. This explains the reason why the coupling length increases with the increase of d/Λ for a given wavelength. According to the above discussion, it is possible to tune the SPSM coupling region to cover the communication window of 1.3 or $1.55 \mu\text{m}$ by further optimizing the structural parameters.

Fig. 7 The dependence of coupling length on wavelength under different values of d/Λ .

3.3 Confinement Loss Characteristics

The confinement losses of even modes for two orthogonal polarizations are also studied. For accurately calculating the confinement loss, an anisotropic PML is applied as the absorbing boundary condition. Due to the small difference of the confinement loss between odd and even modes for the same polarization, only even modes are considered for simplicity. Figure 8 shows the confinement losses of even modes for x and y polarizations as a function of wavelength with 6 and 8 rings of arrays of air holes. The structure parameters Λ , d/Λ , and D/Λ are set to be $2.2 \mu\text{m}$, 0.39 , and 0.97 , respectively. It can be clearly seen that the confinement loss increases with the increase of wavelength for both polarization modes, which occurs because the mode field power is better confined in the dual cores at the short wavelengths. Table 1 lists the values of confinement loss at the wavelength of 1.3 and $1.55 \mu\text{m}$ for x and y polarizations. We find that increasing rings of arrays of air holes N_r can

Fig. 8 Confinement loss of even modes for two polarization modes as a function of wavelength with different rings of arrays of air holes N_r . The dashed and solid lines are for $N = 8$ and $N = 6$.

Table 1 Confinement loss for the PCF coupler.

Polarization mode	Loss at $1.3 \mu\text{m}$ (dB/m)		Loss at $1.55 \mu\text{m}$ (dB/m)	
	$(N_r = 6)$	$(N_r = 8)$	$(N_r = 6)$	$(N_r = 8)$
x polarized even mode	6.9×10^{-1}	3.9×10^{-2}	2.1×10^3	2.9×10^2
y polarized even mode	2.8×10^{-3}	7.7×10^{-5}	4.3×10^{-1}	2.6×10^{-2}

effectively reduce the confinement loss, and the confinement loss of even mode for x polarization is 3 orders of magnitude larger than that for y polarization in SPSM coupling region, which implies that the supermodes in x polarization will be leaking out rapidly.

4 Conclusion and Discussion

In conclusion, we have proposed a SPSM coupler based on the dual-core PCF, and its simple structure may be manufactured under present fabrication techniques. The SPSM coupling region, coupling length, and confinement loss are investigated in detail by using full-vector FEM. The calculated results indicate that the coupling length is about millimeter order of magnitude. It is of interest that the coupling length becomes shorter due to the wider silica bridge of energy transfer, though the separated distance between two cores is enlarged. This may make it convenient to connect with other output devices. Furthermore, the proposed PCF coupler possesses broad SPSM coupling range more than 200 nm , and the SPSM coupling region can be flexibly tuned to cover the communication windows of 1.3 or $1.55 \mu\text{m}$ by optimizing design parameters. Finally, the difference of confinement losses between two polarization modes in SPSM coupling region can be up to 3 orders of magnitude, which implies that one polarization will leak out rapidly.

Acknowledgments

This work was supported in part by the National Natural Science Foundation of China (Grant Nos. 51379042, 51379047, and 51509049), the Fundamental Research Funds for the Central Universities (Grant No. HEUCF150810), and the Postdoctoral Grants of Heilongjiang Province (Grant No. 3236310313).

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