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Bending dual-core photonic crystal fiber coupler

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ABSTRACT

In this paper, we systematically study a designed structure of a bending dual-core photonic crystal fiber (PCF). We propose the controllable wavelength-selective coupling PCF. This coupler allows highly accurate control of the filtering wavelength. The different wavelengths can be selected by controlling the bending radius of the fiber. Coupling characteristics of novel bending wavelength-selective coupling PCF are evaluated by using a vector finite element method and their application to a multiplexer demultiplexer (MUX–DEMUX) based on the novel coupler is investigated. When the fiber length is 4168 μm, the bending radius of PCF couplers for 1.48/1.55 μm, 1.3/1.55 μm, 0.98/1.55 μm, and 0.85/1.55 μm is calculated, respectively, and the beam propagation analysis is performed. Different from the traditional wavelength-selective coupling PCF, the dual-core PCF is bent and it can realize the separation of multiple wavelengths.

1. Introduction

Photonic crystal fibers (PCFs) are well known to possess remarkable features compared to traditional optical fibers. PCFs are divided into two different kinds of fibers, classified by their light-guiding mechanism [1]. The first one, high-index guiding PCF, guides light by a modified form of total internal reflection [2]. On the other hand, the second type of fiber provides guidance by the photonic bandgap (PBG) effect, allowing for novel features such as light confinement to a low-index core [3]. In this paper, we will focus on high-index guiding PCFs. It is well known that PCFs have shown excellent performances in applications such as optical communications, fiber lasers, supercontinuum sources and also fiber sensors, because the design of PCF is very flexible. It allows for the various properties including birefringence [4], chromatic dispersion [5], and nonlinearity [6,7]. Meantime, bending characteristics of PCFs have been investigated theoretically as well as experimentally in some papers, including the bending-induced mode distortion and the bending loss [8,9]. The most of the papers about bending characteristics are based on the single-core fiber. There is one defect in the central region and the light is guided along this defect. A dual-core PCF, introducing adjacent two defects has been proposed, it has been shown that it is possible to use the PCF as compact PCF coupler [10], wavelength MUX–DEMUX [11], polarization splitter [12], and narrow band-pass filter [13]. Many papers about MUX–DEMUX have been reported in the literature [14]. However, a specific length of optical fiber coupler can only achieve a specific wavelength-selection. It cannot realize the separation of multiple wavelengths. Therefore, it is essential to study a controllable PCF coupler that can separate the multiple wavelengths for a specific fiber length.

In this paper, we investigate the bending characteristics of designed dual-core PCF, including bending loss, effective index and coupling length and propose bending dual-core PCF coupler. Results demonstrate that this fiber coupler can accurately control the filtering wavelength. The different wavelengths can be selected by controlling the bending radius of fiber. Theoretical design and analysis of the bending dual-core PCF coupler have been reported in the paper.

We present our systematic study of the designed bending dual-core PCF in this paper, which is organized in the following way: Section 1 gives an overview of the paper and highlights its contribution. Section 2 describes the designed structure and basic theory. Section 3 discusses the modeling results of bending dual-core PCF as a novel fiber coupler design in terms of various performance indicators. Section 4 gives an application in MUX–DEMUX. Section 5 summarizes the key findings.

2. Theory and modeling

The transverse cross section of the dual-core PCF coupler is shown in Fig. 1, the air-holes are arranged in a triangular lattice, where Λ denotes the air-hole pitch, d_1 and d_2 denote the air-hole

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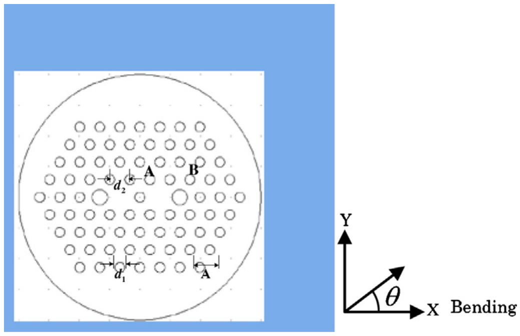

Fig. 1. Cross section of the dual-core PCF.

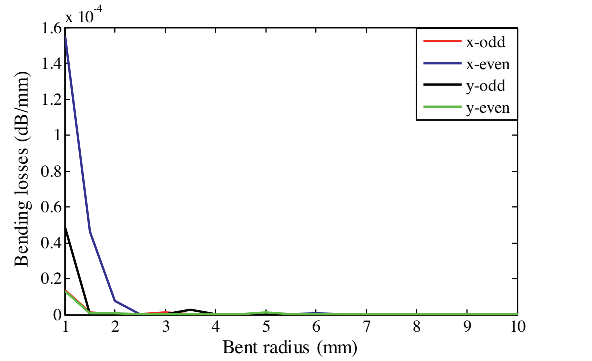

Fig. 2. Bending losses (x-odd, y-odd, x-even, and y-odd) as functions of bent radius.

diameter, θ denotes the angular orientation of the fiber with respect to the bending plane. It consists of two identical cores A and B. The separation between the centers of two cores, A and B, is 2Λ. The transverse cross section of the bending dual-core PCF coupler just introduces two big air-holes in the x-axis direction near the two cores. The structure of this fiber facilitates easy fabrication. The structure parameters are set as $\Lambda = 3.3\ \mu\text{m}$, $d_1/\Lambda = 0.485$, and $d_2 = 2.5\ \mu\text{m}$. The background silica refractive index is assumed to be 1.45 for calculation, and the air refractive index is assumed to be 1.

Here, we simulate the characteristics of this designed PCF structure by the vector finite element method with an anisotropic perfectly matched layer [15]. To study bending effects, we apply the conformal transformation method to convert a bended PCF to its equivalent straight PCF with a modified index profile. The curved fiber was replaced by a straight fiber with an equivalent refractive index distribution [16]:

$$n_{eq}(x, y) = n(x, y) \exp\left(\frac{p}{R}\right) \tag{1}$$

where $p = x$ or y, depending on the bending direction, and R denotes the effective bending radius. According to a well-known formula, the bending loss L_b can be defined as

$$L_b = \frac{2 \times \pi \times 8.686 \times Im(n_{eff})}{\lambda} \tag{2}$$

where n_{eff} denotes the wavelength dependent effective index, $\mathrm{Im}(n_{eff})$ denotes the coefficient of the imaginary part of n_{eff}, and λ denotes the wavelength, respectively. A crucial parameter of the coupling properties is the coupling length L_c of the fiber coupler [17]. The coupling length L_c denotes obtained by using the propagation constants of even mode β_e and odd mode β_o as

$$L_c = \frac{\pi}{\beta_e - \beta_o} \tag{3}$$

When the mode power $P_{in}^{x,y}$ is inputted into the core, the power at the output of the cores $P_{out}^{x,y}$, is calculated as

$$P_{out}^{x,y} = P_{in}^{x,y}\left(1 - \left(\frac{k^2}{\delta^2}\right)\sin^2(\delta z)\right) \tag{4}$$

Note that we have:

$$\delta = \sqrt{\left(\frac{\beta_A - \beta_B}{S}\right)^2 + k^2} \tag{5}$$

where z denotes length of fiber, and k denotes coupling coefficient. β_A and β_B denote the propagation constants of core A and core B, respectively.

3. Results and discussions

We calculate the bending losses and effective indices of the designed dual-core PCF by using the full-vector finite-element method. Fig. 2 shows the bending losses as functions of bending radius at $\theta = 0°$ and operating wavelength $\lambda = 1.55\ \mu\text{m}$. Numerical simulations show that the designed dual-core PCF has low bending losses. The bending loss of the x-even, x-odd, y-even, and y-odd mode is 7.7×10^{-6} db/mm, 8.8×10^{-8} db/mm, 5.77×10^{-7} db/mm, and 5.81×10^{-8} db/mm, respectively, with the bending radius $R = 2$ mm. For the low bending losses, we keep the bending radius $R \geq 2$ mm. By numerical calculation, we find that the effective index changes with the change of bending radius and angular orientation. When $\theta = 0°$, and $\lambda = 1.55\ \mu\text{m}$, the effective indices (x-odd, y-odd, x-even, and y-odd) as functions of bending radius are shown in Fig. 3(a). From the figure, we can clearly see that the effective indices of x- and y-even mode decrease and the effective indices of x- and y-odd mode increase with the decrease of bending radius. The difference of effective index between odd mode and even mode becomes smaller relatively with the increase of bending radius. The

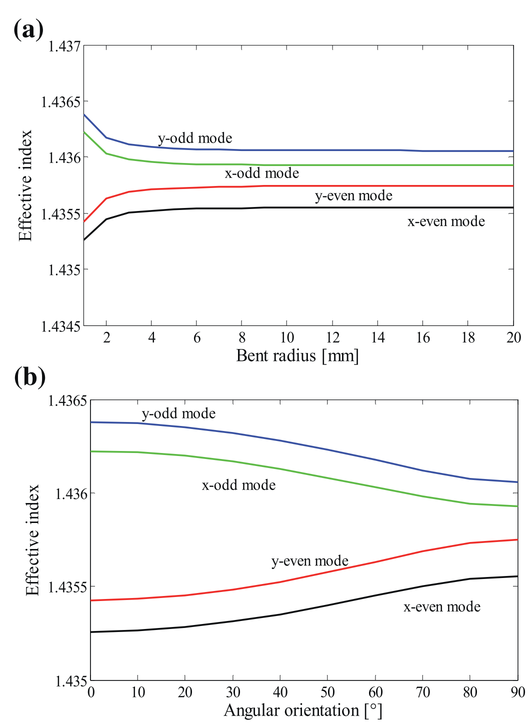

Fig. 3. Effective index (x-odd, y-odd, x-even, and y-odd) as functions of (a) bending radius and (b) angular orientation. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)