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Design of short polarization splitter based on dual-core photonic crystal fiber with ultra-high extinction ratio

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A B S T R A C T

A novel (to our knowledge) type of dual-core photonic crystal fiber (PCF) based polarization splitter is proposed. The effects of the geometrical parameters on the performances of the polarization splitter are studied numerically based on full vector finite element method (FEM). Finally, an optimal design based on the proposed dual-core PCF with a length of 0.401 mm is achieved, the extinction ratio (ER) of the splitter can reach 110.1 dB at the wavelength of 1.55 μm, and the bandwidth of ER over 20 dB and 10 dB can be as wide as 140 nm and 200 nm, respectively. This polarization splitter proposed in this paper provides a new structure for designing a splitter with short length, high ER and wide bandwidth simultaneously.

1. Introduction

Polarization splitters, as an important kind of components in optical systems, can split one light beam into two light beams in orthogonal polarization states, and have bright prospects of applications in optical communication systems, optical fiber sensing system and so on [1,2]. The dual-core fibers are usually used as polarization splitter since a polarization splitter based on a dual elliptical cores optical fiber was demonstrated in 1990 [3]. However, the fabrication technologies of traditional dual-core fibers are very complex, and they are faced with many defects. The pursuit of polarization splitter with short length, high extinction ratio (ER), wide bandwidth and flattened dispersion has long been a subject of interests for researchers. The appearance of photonic crystal fibers (PCFs), gave us a chance to realize this goal [4].The PCFs, also known as micro-structure fibers or holey fibers, have attracted significant attention in the past several years because of their outstanding optical properties and flexibility in structure design. PCFs can get many powerful properties such as endless single mode [5], high birefringence [6], large mode area [7], high nonlinearity and controllable chromatic dispersion [8,9], by changing the cladding arrangement.

There are mainly two kinds of PCFs based polarization splitters according to the mechanisms: one kind are polarization splitters based on the phenomenon of resonant tunneling of three-core PCFs [10]; the other kind are based on the highly birefringent dual-core PCFs [11]. The high birefringence in the dual-core PCFs give rise to an adequate difference between the coupling lengths of two orthogonal polarization states, and the two polarization states can be separated from each other in two cores.

There are many types of polarization splitters based on PCFs have been reported in literature up to now. In 2003, Zhang and Yang proposed a polarization splitter based on dual-core PCFs for the first time, whose ER at the wavelength of 1.55 μm can reach −11 dB with a length of 1.715 mm [12]. In 2013, Lu et al. proposed a ultra-broadband polarization splitter based on a three-core PCF, the splitter had a bandwidth as wide as 300 nm with an ER better than −20 dB, and the ER can reach −30 dB at the wavelength of 1.55 μm with a length of 84.7 mm [13]. In 2014, Sheng et al. proposed a compact polarization splitter based on dual-elliptical-core PCF, the splitter had the length of 775 μm and up to 50 dB ER at the wavelength of 1.55 μm,and the bandwidth could be 32 nm with the ER over 20 dB [14]. Fan et al. proposed a polarization splitter based on dual-core tellurite glass PCF in two communications bands, in which a −81.0 dB of ER was achieved at the wavelength of 1.55 μm with a length of 14.662 mm, but the bandwidth was narrowed to 13.0 nm as the ER better than −10 dB [15]. Bao et al. proposed a polarization splitter based on a PCF with high birefringence and low dispersion, the splitter had the length of 2.481 mm and up to −55.3 dB ER at the wavelength of 1.31 μm, and the bandwidth was 8 nm at the ER of −10 dB [16]. Jiang et al. proposed a polarization splitter based on a new type of dual-core PCF, the splitter had the length of 119.1 um and up to 118.7 dB at the wavelength of 1.55 μm, and the bandwidth could be 249 nm

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with the ER over 20 dB, thus this design had short length, high ER and wide-bandwidth simultaneously compared with the designs mentioned above [17].

These designs mentioned above have their own features and advantages. However, most of these designs in literature except Haiming Jiang's do not have the features of short length, high ER and wide-bandwidth simultaneously. There's still a lot of work need to be done to improve the performance of polarization splitters for meeting the demands of optical systems.

In this paper, a simpler structured polarization splitter base on a dual-core PCF is proposed. The effects of the geometrical parameters on the performances of the polarization splitter are studied numerically based on the full-vector finite element method. The properties of the dual-core PCF based splitter are improved by introducing an elliptical hole with low-index material-doped between the two cores and adjusting the cladding structures properly. Finally, an optimal design with a length of 0.401 mm is achieved, the ER of the splitter can reach 110.1 dB at the wavelength of 1.55 μm, and the bandwidth of ER over 20 dB and 10 dB can be as wide as 140 nm and 200 nm, respectively, which covers the S+C+L wavelength bands.

2. Theory and design

In this design process, a full-vector finite element method (FEM) [18] has been used to characterize the proposed PCF. The FEM solves the Maxwell equations directly to best approximate the value of the effective refractive index. And it can distinguish the transmission mode in fiber accurately and can be used to study PCFs with different structures.

The cross section of the proposed dual-core PCF is shown in Fig. 1. The air holes are arranged in hexagonal lattice in silica background with lattice pitch $\Lambda=2$ μm, the two cores A and B are formed by replacing two air holes. The diameters of different air holes in the cladding are represented by d_1, d_2, d_3, d_4, respectively, a and b denote the lengths of the long and short shaft of elliptical hole arranged between core A and core B, and the ellipticity can be defined as $\eta=a/b$. The refractive index of the silica cladding and the air is 1.444 (at 1550 nm wavelength) and 1.0, respectively. The refractive index of the low-index material-doped elliptical core between core A and core B is denoted by n_c.

According to the mode coupling theory, the coupling mechanism in dual-core PCFs can be described by interference effect between supermodes. There are four fundamental supermodes exciting in the dual-core PCF: the odd mode and even mode for x-polarization and y-polarization state, which are shown in Fig. 2. The odd mode and even mode with same polarization direction will produce mode coupling when they are propagating along the fiber [19].

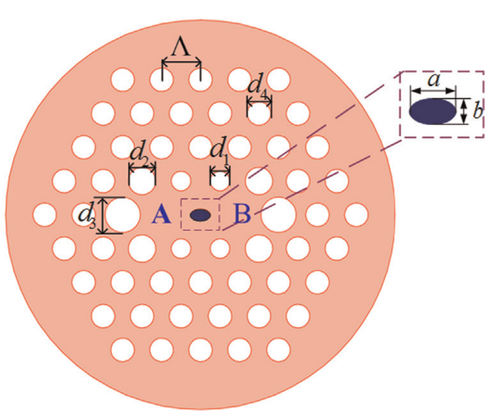

Fig. 1. Cross section of the proposed dual-core PCF.

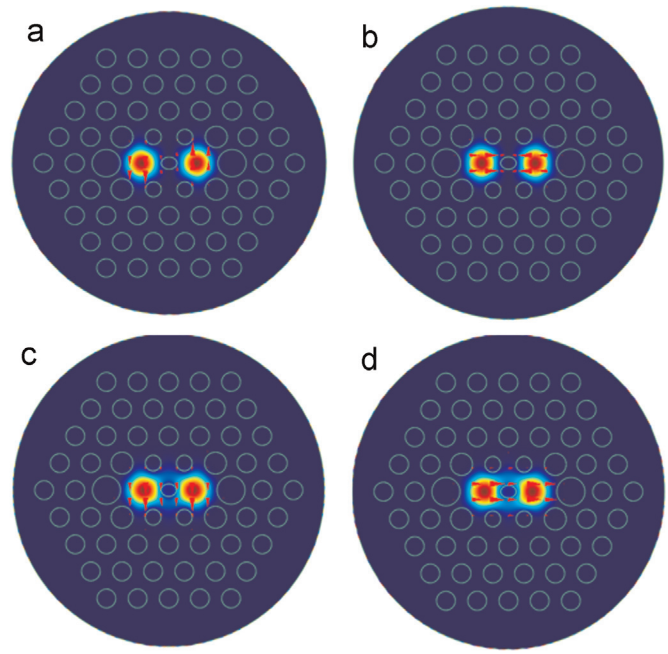

Fig. 2. Power flow distributions of the four supermodes in the proposed dual-core PCF at the wavelength of 1.55 um: (a) the y-polarized odd mode; (b) the x-polarized odd mode; (c) the y-polarized even mode; (d) the x-polarized even mode.

A crucial parameter of the coupling properties of dual-core PCFs is coupling length L_c, which denotes the length of a complete power transformers from one core to the other, is defined as follows [20]:

$$L_c^i = \frac{\pi}{\beta_{even}^i - \beta_{odd}^i} = \frac{\lambda}{2\left(n_{even}^i - n_{odd}^i\right)} \tag{1}$$

where $i=x,y$; β_{even}^i, β_{odd}^i, n_{even}^i, n_{odd}^i denote the propagation constants and effective indexes of the even and odd modes for x and y polarization states, respectively. And λ is the wavelength of light. The coupling length is the shortest distance that one polarized light can propagate from one core to the other, the shorter the coupling length is, the stronger the coupling strength is between the two cores.

When a fundamental mode power is inputted into the core A, the output powers in the output ports after propagating a distance of L are calculated as [21]:

$$P_{out}^i = P_{in}^i \cos^2\left(\frac{\pi}{2}\frac{L}{L_c^i}\right) \tag{2}$$

where $i=x,y$; P_{in}^i, P_{out}^i denote the input powers and output powers of x and y polarization modes at the input ports and output ports, respectively.

The extinction ratio (ER) is a key parameter for the polarization splitter, and can be used to describe the splitting ability of different polarization states at one output port. The ER is defined as follows [22]:

$$ER = 10\lg\frac{P_{out}^y}{P_{in}^x} \tag{3}$$

where, P_{out}^x, P_{out}^y denote the output power for x and y polarization modes at the output ports, respectively. The higher the absolute value of ER is, the more the polarization states completely separated. In fact, when the ER reaches 20 dB, it means that the power for one polarization state is 100 times higher than that for the other polarization state, thus the two polarization states can be