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Few-mode and large-mode-area fiber with circularly distributed cores

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ABSTRACT

In this paper, a novel few-mode large-mode-area fiber is proposed. This type of fiber consists of 11 conventional cores and 8 air-hole cores circularly arranged around the center core. Few-mode condition equal to strict dual-mode here is available by appropriate adjusting on corepitch, relative refractive index difference and core radius. Large effective area of fundamental mode around 1403.561 μm^2 could be achieved by optimization of structural parameters. Bending loss less than 10^{-3} dB/m is realized when effective area is over 1400 μm^2.

1. Introduction

Transmission capacity limit of current optical communication system is the crucial problem with exponential data growth. Conventional single mode fiber (SMF) is not robust enough to deal with approaching data traffic jam [1,2]. Space division multiplexing (SDM) is regarded as a potential candidate to further increase transmission capacity due to its multiple transmission paths realized by either multi-core fiber (MCF) or few-mode fiber (FMF) [3–6]. Besides, mode-division multiplexing (MDM) and orbital angular momentum (OAM) transmission based on the concept of SDM have also been proposed in optical fiber communication system [5]. Recently transmission capacity over 100 Tb/s has been achieved by using MCF with other multiplexing technologies, which is a great encouragement for massive researchers [7–10]. MCF has drawn a number of attentions due to its flexible design freedom including core numbers, corepitch, core radius, and refractive index difference between core and cladding [11]. Most researches focus their attention on uncoupled MCF in order to get low crosstalk [12]. However, another type of MCF with coupled core structure receives less concern. The latter could realize large-mode-area characteristics which is helpful to mitigate nonlinearity [13]. But we must take care of bending influence on transmission loss and effective area. There is a tradeoff between large effective area and low bending loss.

In this paper, a novel few-mode large-mode-area fiber with low bending loss is proposed. Different from conventional hexagonally packed fiber structure, the fiber structure here is arranged circularly around the center core, which has a larger adjusting range of corepitch to realize large-mode-area. There are only two degenerate propagating modes of HE_{11} and HE_{21} by introducing air-hole cores symmetrically arranged on two sides of center core, which leads to a leakage channel for circular symmetry field of TE and TM modes and increases propagating loss of high order modes. Few-mode condition can be available by adjusting fiber parameters. Large effective area about 1403.561 μm^2 of fundamental mode is achieved by optimizing fiber parameters when keeping strict dual-mode condition. In addition, bending loss less than 10^{-3} dB/m is available when effective area is over 1400 μm^2.

2. Fiber structure and mode property

The cross section schematic of two dimensional (2D) proposed fiber structure is shown in Fig. 1. The fiber consists of 19 cores in total, where 11 of them are conventional cores with high refractive indices and 8 of them are air-hole cores with refractive indices equal to 1.000. Different from conventional hexagonally distributed MCF, the cores are arranged circularly from the fiber center. The diameter of each core is d, and the corepitch between adjacent cores of the first circle including 6 cores is Λ. As seen from Fig. 1, the second circle of 12 cores start from the same horizontal level as that of first circle, and the distance between two cores of two circles' start points in horizontal direction is also Λ. The refractive index of conventional core is n_1, the refractive index of cladding is n_2, and the relative refractive index difference is $\Delta = (n_1^2 - n_2^2)/(2n_1^2)$. Besides, the operation wavelength is λ.

The guided modes propagating along the fiber must obey the law $n_2 < n_{eff} < n_1$, where n_{eff} is the effective refractive index of guided

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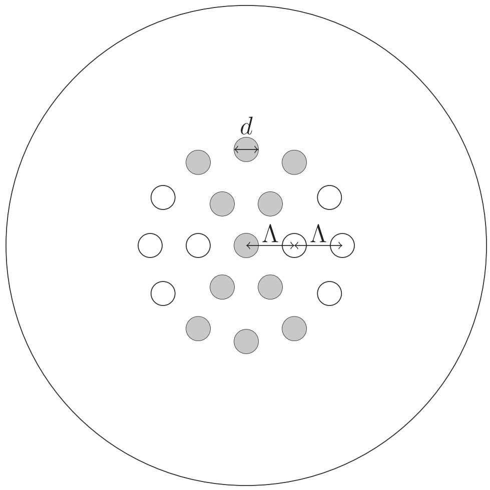

Fig. 1. Cross section schematic of proposed fiber structure.

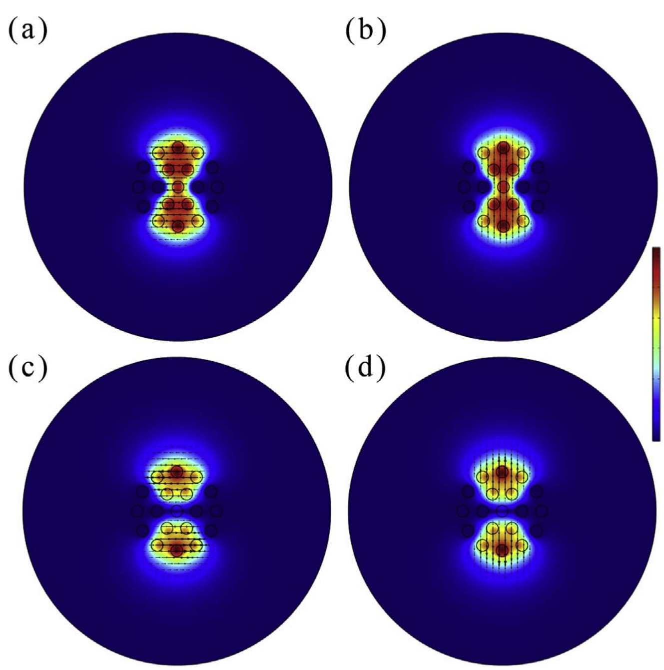

Fig. 2. Mode field and electric vector distributions. (a) and (b) HE_{11} mode and (c) and (d) HE_{21} mode.

mode. The mode whose n_{eff} is lower than cladding refractive index n_2 is going to be cut off. In conventional silica-based SMF, n_2 is set to be 1.444, while n_1 is set to be 1.447 when λ=1.55 µm. In this fiber structure, the air-hole cores arranged symmetrically on both sides open a leakage channel for TE mode and TM mode, and increase propagating loss of high order modes, thus reducing the total mode number [14]. We use the commercial software Comsol Multiphysics based on fully vectorial FEM to investigate the mode property. The few-mode here could be also called strict dual-mode, which only includes two degenerate modes HE_{11} and HE_{21}. Fig. 2 illustrates the mode field and electric vector distributions of two degenerate modes with core radius a equal to 2.4 µm. From the mode field profiles, one can believe that such fiber structure can support two modes transmission. Meanwhile, the two modes both include *x*-polarization mode and *y*-polarization mode.

To further investigate the few mode characteristic of the fiber, we scan the full C and L band to get the effective index of each propagating mode. The relationship between n_{eff} and λ is shown in Fig. 3. The effective refractive indices of TE_{01}, TM_{01} and high order mode, which is the first cut-off mode next to TM_{01} mode, are also plotted in Fig. 3.

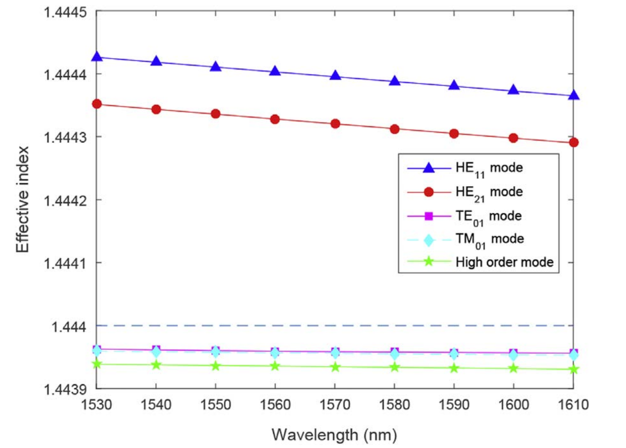

Fig. 3. The relationship between effective index and operating wavelength of each mode.

From Fig. 3, it can be clearly seen that effective refractive indices of TE_{01}, TM_{01} and high order mode are lower than that of the cladding, so they cannot exit in the fiber. As a result, the fiber supports only HE_{11} mode and HE_{21} mode over C + L band. That is why we called it a strict dual-mode fiber.

To estimate the effective area A_{eff} of fundamental mode, we adopt the following formula [15]:

$$A_{eff} = \frac{\int (\underline{E}\underline{E}^{*}\mathrm{d}A)^2}{\int (\underline{E}\underline{E}^{*})^2\mathrm{d}A} \tag{1}$$

where $\underline{E}$ represents the electric field and $\underline{E}^{*}$ represents the complex conjugate.

3. Structural parameters effect on mode area

To pursuit large effect area of fundamental mode (HE_{11} mode) within few-mode condition, we investigate three structural parameters effect on effective area. Corepitch Λ, relative refractive index difference Δ and core radius a are three key structural factors. At the same time, we investigate the number of propagating mode when wavelength is set to be 1.55 µm.

We first fix relative refractive index difference Δ to be 0.0021, and core radius a to be 2.4 µm. The cladding radius is set to be 62.5 µm unless other specified. The effective index of different mode as variation of Λ, and effective area of fundamental mode as variation of Λ are depicted in Fig. 4(a) and (b), respectively. From Fig. 4(a), we can find that the number of guided mode in the fiber still keeps two effective indices and both linearly decrease with Λ's ranging from 6.4 µm to 10.0 µm. That is to say, there are HE_{11} mode and HE_{21} mode existing altogether, which satisfies strict few-mode condition. The effective area of fundamental mode almost increase linearly with the increase of Λ as seen from Fig. 4(b). The maximum value of effective area could reach 1000 µm^2.

We then explore the influence of relative refractive index difference Δ on mode number and effective area. Fiber structural parameters are set as follows: Λ=9.6 µm and a=2.4 µm. Fig. 5 shows n_{eff} and effective area as functions of various Δ. Fig. 5(a) clearly demonstrates that the supporting mode number is two with the change of Δ, and effective indices of the two modes gradually increase when Δ increases. Fig. 5(b) reveals that effective area decreases with increase of Δ. For a small Δ, we can get a large value of effective area over 1000 µm^2.

At last, we analyze the effect of core radius a on n_{eff} and effective area assuming that Λ=9.6 µm and Δ = 0.0021. The relationship between n_{eff} and a is illustrated in Fig. 6(a), and the relationship between effective area and a is displayed in Fig. 6(b). One can see that only two modes could propagate along the fiber when a ranges from 1.8 µm to 2.5 µm, and their effective indices increase slightly with the increase of