# **PHOTONICS** Research

## Polarization-maintaining few mode fiber composed of a central circular-hole and an elliptical-ring core

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We propose a novel waveguide design of polarization-maintaining few mode fiber (PM-FMF) supporting  $\geq 10$  non-degenerate modes, utilizing a central circular air hole and a circumjacent elliptical-ring core. The structure endows a new degree of freedom to adjust the birefringence of all the guided modes, including the fundamental polarization mode. Numerical simulations demonstrate that, by optimizing the air hole and elliptical-ring core, a PM-FMF supporting 10 distinctive polarization modes has been achieved, and the effective index difference  $\Delta n_{\text{eff}}$  between the adjacent guided modes could be kept larger than  $1.32 \times 10^{-4}$  over the whole C + L band. The proposed fiber structure can flexibly tailored to support an even larger number of modes in PM-FMF (14-mode PM-FMF has been demonstrated as an example), which can be readily applicable to a scalable mode division multiplexing system. © 2017 Chinese Laser Press

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#### **1. INTRODUCTION**

In the emerging era of big data and its applications, data amounts have been exploding, and the workload for optical networks and data centers (DCs) is approaching its physical limits [1]. It is reported that the current transmission system based on traditional single-mode fibers (SMFs) is rapidly reaching its ultimate capacity following the nonlinear Shannon limit [2]. In order to solve these imminent traffic bottlenecks, spacedivision multiplexing (SDM) transmissions have been recently intensively investigated as a viable measure [3]. The multicore fiber (MCF) [4-6], as one of the spatial multiplexing techniques, is the most straightforward solution in SDM. However, there are a great deal of technical challenges in the design and manufacture of high-core-count, low-loss, and low-crosstalk MCF. It is increasingly challenging to couple signals in and out of each core because the cores have to be closely packed in a scalable MCF [7]. The few mode fiber (FMF) [8-10] acts as another practical avenue in SDM, due to its mass-fabricated capability and low loss connectivity with conventional SMFs. The crosstalk among propagation modes is being regarded as the most crucial issue in FMF data links. To solve this issue, two different methods have been proposed. One is using the multiple input multiple output (MIMO) digital signal processing (DSP) at the receiver to electronically recover the signals carried over guided modes [11]. The drawback of this technique is that the complexity of MIMO scales up nonlinearly with the number of modes, easily depleting the DSP capacity and its electric power consumption. The other method is using specially designed FMF with large difference in the effective indices  $\Delta n_{\rm eff}$  between the adjacent propagation modes to fundamentally suppress the mode coupling [12]. Previous experiments have proved that the crosstalk can be efficiently suppressed when the effective index difference is larger than  $\sim 10^{-4}$  [13]. The latter method would have a clear advantage in energy efficiency; therefore, it would be especially suitable for the shortreach transmission in the DCs. This is the motivation of our research to design FMF flexibly scalable with a high  $\Delta n_{\rm eff}$  for guided modes.

Elliptical core fibers (ECFs) [14–16] have been widely used as a polarization maintaining fiber (PMF), provided an efficient form-birefringence in the guided modes. In ECF, the effective index difference  $\Delta n_{\text{eff}}$  between the adjacent LP modes can be made large by increasing the refractive index contrast between the core and the cladding. In recent years, attempts to use ECF as a transmission medium in mode division multiplexing (MDM) has been reported to increase the system capacity and the spectral efficiency. In 2012, a three-mode  $(LP_{01}, LP_{11e}, and$ LP<sub>02</sub>) transmission over ECF without using MIMO technique was reported [13]. In 2015, the first few-mode SDM transmission of real-time 10 Gb/s Ethernet traffic without coherent detection or MIMO-DSP over a 0.5 km elliptical-core FMF was achieved [17]. However, prior reports have suffered from the scalability issue such that all the ECFs mentioned above guided only a few higher-order modes, which may limit its overall capacity. Although higher birefringence in solid core ECF is helpful to increase the differences among the effective indices of the guided modes, it also cuts off some higher-order modes. Therefore, there is usually a trade-off between the number of guided modes and the achievable effective index difference [18]. In December 2015, an 8-mode polarization-maintaining (PM)-FMF with an elliptical-ring core had been reported [18]. This design successfully avoided the trade-off, achieving the highest number of PM modes thus far. However, among the 10 guided vector modes, the two fundamental polarization modes were still degenerate; thus, the full spatial mode diversity has not yet been efficiently exploited. References [19,20] have shown that the birefringence of the elliptical solid core fiber can be increased by an order of magnitude by placing an elliptical air hole in the fiber core center. However, the control of ellipticity of the central air hole would be a great challenge in practical fabrication processes.

In this paper, we propose a new FMF structure that can fully exploit the polarization mode splitting by using a circular air hole in the center, which also will facilitate fabrication stability. The structure endows a new degree of freedom to adjust the birefringence of all the guided modes, including the fundamental polarization mode. Thorough vectorial mode analyses showed that the two fundamental polarization modes can be effectively separated, and the minimum  $\Delta n_{\rm eff}$  of  $1.32 \times 10^{-4}$ among the 10 guided modes is attainable over the whole C + L band. We also confirmed potential scalability of this structure, such that proposed fiber structure also could be extended to 14-mode PM-FMF.

The rest of the paper is organized in three sections. In Section 2, the schematic topology of the proposed PM-FMF is presented. In Section 3, the impact of the air hole size on the  $\Delta n_{\text{eff}}$  and modes properties is investigated and analyzed in detail. Finally, a brief conclusion is given in Section 4.

#### 2. SCHEMATIC TOPOLOGY

The cross section of the proposed 10-mode PM-FMF is shown in Fig. 1, which comprises a circular air hole in the center, a circunjacent elliptical-ring core, and a circular cladding. The background material is pure silica, and the ring core is GeO<sub>2</sub>-doped silica. Moreover, a number of parameters are used to describe the fiber geometric structure.  $d_{cladding}$  denotes the cladding diameter and r denotes the air hole radius. The outer radii of a along the x and y axes are  $b_x$  and  $b_y$ , respectively, and the inner radii of elliptical ring are  $a_x$  and  $a_y$ . The ratio,

**Fig. 1.** Cross section of the proposed elliptical-ring core fiber with a central circular air hole. Key waveguide parameters are the cladding diameter  $d_{\text{cladding}}$ , the air hole radius *r*, the major axes of the ring core,  $b_x$  and  $b_y$ , the minor axes,  $a_x$  and  $a_y$ , the cladding's and core's materials, SiO<sub>2</sub> and GeO<sub>2</sub>-doped SiO<sub>2</sub>.

 $\eta = b_x/b_y = a_x/a_y$ , represents the ellipticity.  $\rho$  is the ratio between  $a_{x,y}$  and  $b_{x,y}$ ,  $\rho = a_x/b_x = a_y/b_y$ .

Except for the air hole radius r, all the other parameters of the fiber are set to be the same as the 8-mode PM-FMF with the optimal value as in Ref. [18], that is,  $n_{\rm ring} = 1.474$ ,  $n_{\rm cladding} = 1.444$ ,  $d_{\rm cladding} = 125 \ \mu m$ ,  $\eta = 1.4$ ,  $\rho = 0.67$ , and  $b_x = 5.06 \ \mu m$ . Here, numerical calculations were done with a finite element mode solver (COMSOL).

#### 3. IMPACT OF AIR HOLE SIZE ON THE DIFFERENCE OF THE EFFECTIVE REFRACTIVE INDEX AND ANALYSIS

In this section, the main work is to find out the optimum value of the air hole size, so as to achieve the 10-mode PMF. The impact of the air hole size on the mode properties of the proposed fiber was carefully studied, and the detailed analysis also was performed.

Before setting out to do this work, we first noticed that the number of the guided modes decreases with the increase of the size of the air hole through the preliminary simulations. The reason may be that the air hole slightly impairs the effective refractive index of the ring core, thus leading some higher-order vector modes easily to leak out. To maintain the number of the vector modes supported by the fiber to be 10, either the ring and the cladding should be increased. Here, we choose to enlarge  $n_{\text{ring}}$  from the reference value 1.474–1.478 to reach our target just by increasing the GeO<sub>2</sub> doping rate from 20.95% to 23.75%.

Then, the next step is to search for the optimum value of the air hole radius r. Figure 2(a) shows the  $\Delta n_{\text{eff}}$  between all adjacent guided modes as a function of air hole radius r at the wavelength of 1550 nm with  $n_{\text{ring}} = 1.478$ ,  $n_{\text{cladding}} = 1.444$ ,  $d_{\text{cladding}} = 125 \,\mu\text{m}$ ,  $\eta = 1.4$ ,  $\rho = 0.67$ , and  $b_x = 5.06 \,\mu\text{m}$ . In this case, the corresponding value of  $a_y$  is 2.42  $\mu$ m. Because the value of the air hole radius r cannot be larger than that of  $a_y$ , in our simulations, we increase the air hole radius r from 0  $\mu$ m to 2  $\mu$ m with a step size of 0.1  $\mu$ m. For convenience, these 10 guided modes from mode  $1(m_1)$  to mode  $10(m_{10})$  are arranged by the order of their gradually decreased effective refractive index ( $n_{\text{eff}}$ ). Another thing to note is that, in this figure, the lines with symbols are  $\Delta n_{\text{eff}}$  between orthogonal polarization of the



**Fig. 2.** In the situation that  $n_{\text{ring}} = 1.478$ ,  $n_{\text{cladding}} = 1.444$ ,  $d_{\text{cladding}} = 125 \,\mu\text{m}$ ,  $\eta = 1.4$ ,  $\rho = 0.67$ ,  $b_x = 5.06 \,\mu\text{m}$ , and  $\lambda = 1.55 \,\mu\text{m}$ : (a) the  $\Delta n_{\text{eff}}$  between the 10 adjacent modes as a function of the air hole radius *r*; (b) magnified image of the light orange rectangle in (a); (c) the  $\Delta n_{\text{eff}}$  between the first seven adjacent modes with increasing of *r*; (d) the  $\Delta n_{\text{eff}}$  between the last four adjacent modes with increasing of *r*. Note that the lines with symbols are the  $\Delta n_{\text{eff}}$  between orthogonal polarization of the same mode (modal birefringence), while the lines without symbols are the mode group separation.

same mode (modal birefringence), while the lines without symbols are the mode group separation.

Figure 2(b) is the partial enlarged detail of Fig. 2(a), and it is easy to find that, if the air hole radius *r* is within the range from 1.5 to 1.84 µm, the minimum  $\Delta n_{\text{eff}}$  among all guided modes can be larger than 10<sup>-4</sup>, which indicates its robustness to the air hole size. Especially, when r = 1.7 µm, the minimum  $\Delta n_{\text{eff}}$  can reach to the highest value of  $1.37 \times 10^{-4}$ . Thus, 10 guided modes can be completely separated by the method of adding a circular air hole of appropriate size in the fiber center.

Next, further research is carried out to explain how the air hole readjusts the  $n_{\rm eff}$  of the 10 guided modes. In order to get a better view, Fig. 2(a) is divided into two parts, depicted in Figs. 2(c) and 2(d), respectively. The  $\Delta n_{\rm eff}$  of the first seven adjacent lower-order modes are shown in Fig. 2(c), and the rest are shown in Fig. 2(d).

From Fig. 2(c), it is obvious that the  $\Delta n_{\rm eff}$  between the nondegenerated LP modes decrease quickly as r increases, as represented by the two black curves. On the contrary, the  $\Delta n_{\rm eff}$ between these polarization modes gradually increase as r increases, which are denoted by the three green curves. The blue curve represents the  $\Delta n_{\rm eff}$  between the two degenerate modes of LP<sub>11</sub> rather than two polarization modes, which also increases with r. In summary, for the seven lower-order modes of the fiber, the air hole can slightly reduce the  $\Delta n_{\rm eff}$  between nondegenerated modes and meanwhile enlarge the  $\Delta n_{\rm eff}$  between degenerate modes, especially the  $\Delta n_{\text{eff}}$  between the two fundamental polarization modes,  $LP_{01}^x$  and  $LP_{01}^y$ .

On the other hand, the three red curves in Fig. 2(d) show different trends from that of the curves in Fig. 2(c). But they follow a common process of first dropping and then rising up. In particular, the curve of the  $\Delta n_{\rm eff}$  between mode 8 and mode 9 experiences this process twice. In order to clarify the cause of the difference in Figs. 2(c) and 2(d), we perform a series of detailed analyses and find that the main reason is that the three red curves represent the  $\Delta n_{\rm eff}$  between the four degenerate modes of LP<sup>21</sup>, which can transform into each other as *r* increases. During the transformation, there will be a situation that certain two modes of them become more and more alike to each other, resulting in the decrease of  $\Delta n_{\rm eff}$  between these two modes. At last, the two modes will differ from each other, leading to their  $\Delta n_{\rm eff}$  gradually increasing.

Figure 3 shows the process of transformation for all guided modes along with the increasing of air hole radius *r*. It is clear that the order of the first six modes is fixed no matter how the air hole radius *r* increases, but the order of the last four LP<sup>21</sup> degenerate modes is constantly changing. For the situation without air holes, mode 7, mode 8, mode 9, and mode 10 represent LP<sup>*x*</sup><sub>21*a*</sub>, LP<sup>*y*</sup><sub>21*b*</sub>, and LP<sup>*y*</sup><sub>21*b*</sub>, respectively. When air hole radius *r* equals 0.7 µm, transformation between LP<sup>*y*</sup><sub>21*a*</sub> mode and LP<sup>*x*</sup><sub>21*b*</sub> mode is completed. It can be inferred that there must be a minimum value of  $\Delta n_{\text{eff}}$  between mode 8 and mode 9 before the value of r = 0.7 µm, where the two modes



**Fig. 3.** Transverse electrical fields, amplitudes, and directions of the vector modes at 1.55  $\mu$ m for different sizes of air hole: (a)  $r = 0 \ \mu$ m, (b)  $r = 0.7 \ \mu$ m, (c)  $r = 0.9 \ \mu$ m, (d)  $r = 1.2 \ \mu$ m, and (e)  $r = 1.7 \ \mu$ m.

are most similar to each other. This inference is verified by the result shown in Fig. 2(d), in which the first minimum  $\Delta n_{\text{eff}}$  between mode 8 and mode 9 is obtained at  $r = 0.6 \,\mu\text{m}$ .

As *r* increases from 0.7 to 0.9 µm, the transformation between  $LP_{21a}^{y}$  mode and  $LP_{21b}^{y}$  mode is realized. Again, notice that  $LP_{21a}^{y}$  is mode 9 and  $LP_{21b}^{y}$  is mode 10. Thus, there is also a minimum  $\Delta n_{eff}$  between mode 9 and mode 10 near the value of r = 0.9 µm, as illustrated by the curve of mode 9-mode 10 in Fig. 2(d). Similarly, there is a valley value of  $\Delta n_{eff}$  between mode 7 and mode 8 as well, especially, when r = 1.7 µm, mode 8 and mode 9 perform a new round of interchange; thus, the curve of mode 9-mode 10 reaches another minimum value.

The modal wavelength dependency of the designed fiber over the whole C + L band also is investigated when the air



**Fig. 4.** (a) Effective refractive indices  $(n_{\rm eff})$  of all guided modes. (b) Chromatic dispersions of all guided modes. (c)  $\Delta n_{\rm eff}$  between all adjacent guided modes, as a function of the wavelength of  $\lambda$ , for the 10-mode PMF with  $r = 1.7 \ \mu m$ ,  $n_{\rm ring} = 1.478$ ,  $n_{\rm cladding} = 1.444$ ,  $d_{\rm cladding} = 125 \ \mu m$ ,  $\eta = 1.4$ ,  $\rho = 0.67$ , and  $b_x = 5.06 \ \mu m$ .

hole radius *r* is fixed at the optimized value of 1.7  $\mu$ m. The effective refractive indices and chromatic dispersions of all the 10 guided modes as a function of wavelength were calculated and are shown in Figs. 4(a) and 4(b), respectively. In the simulation, we include material dispersion effects in precise calculation of the effective indices of the guided modes, by using the mixed Sellmeier equation for the elliptical-ring core and the cladding [21]. The maximum chromatic dispersion for all guided modes is about -60 ps/km/nm over the C + L band, indicating that the modal dispersions can be neglected when applied in short-reach optical interconnects. The minimal  $\Delta n_{eff}$  between all adjacent guided modes over the whole C + L band is  $1.32 \times 10^{-4}$ , as in Fig. 4(c).



Fig. 5. Transverse electrical fields, amplitudes and directions of the vector modes at 1.55  $\mu$ m for the optimum air hole radius  $r = 1.8 \mu$ m.

Furthermore, by increasing the elliptical ring width (here, only the parameter  $b_x$  is increased from 5.06 to 5.46  $\mu$ m, and all the other parameters are the same as that of the



**Fig. 6.** (a) Effective refractive indices  $(n_{\text{eff}})$  of all guided modes. (b) Chromatic dispersions of all guided modes. (c)  $\Delta n_{\text{eff}}$  between all adjacent guided modes, as a function of the wavelength of  $\lambda$ , for the 14-mode PMF.

10-mode FMF) and bringing in an air hole with the size from 1.7 to 1.88 µm, a 14-mode PMF also could be obtained. We choose the air hole size r = 1.8 µm as the final design. Figure 5 is the transverse electrical fields of all the guided modes for the 14-mode PMF. Figures 6(a) and 6(b) are the effective refractive indices and chromatic dispersions of all the 14 guided modes as a function of the wavelength, respectively. It is obvious that the maximum chromatic dispersion for all guided modes is about -70 ps/km/nm over the C band. Besides, the  $\Delta n_{\rm eff}$  between all the adjacent guided modes can be larger than  $1.2 \times 10^{-4}$  over the whole C + L band, as shown in Fig. 6(c). Thus, we believe that our proposed method is highly promising for the design of PMF with more modes, thus enabling the dense SDM transmission.

For the fabrication of this kind of fiber, one possible way is to use the following steps to achieve it. First, a pure silica preform is prepared and cut to provide two flat surfaces. Second, the ring-shaped germanosilica core layers are deposited over the prepared preform by the conventional modified chemical vapor deposition process. Third, the two flat surfaces flow to form a circular shape at a high temperature, leaving behind an elliptical-ring germanosilica core. Fourth, a circular air hole is drilled in the preform center, and then the final preform is drawn to fiber. Though, for the elliptical-ring hollow core fiber, the high drawing temperature tends to seal the central air hole, but by careful control of the temperature and tension at the drawing process, the hole can be maintained and prone to have a circular shape due to the built-in positive pressure [20].

#### 4. CONCLUSIONS

In conclusion, we proposed and numerically demonstrated a mode-number scalable PM-FMF by utilizing an elliptical-ring core FMF assisted with a central circular air hole. The impact of the air hole size on the  $\Delta n_{\rm eff}$  and properties of all guided modes are thoroughly investigated. Theoretical results show that a 10 distinctive polarization mode FMF has been achieved, and the minimum  $\Delta n_{\rm eff}$  among all guided modes can reach  $1.32 \times 10^{-4}$ over the whole C+L band. The maximum chromatic dispersion for all propagation modes is less than |-60| ps/km/nm, not affecting the normal use of the fiber in the short-distance transmission. Additionally, a 14-mode PMF also was obtained by the same method proposed in the paper. We believe this method can be further applied to design PMF supporting more modes. Meanwhile, we hope the high performance of the 10-mode and 14-mode PMFs can be used as a promising transmission medium and play

an important role in the future bandwidth intensive high-capacity DCs.

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