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Abstract: This paper proposes a novel refractive index profile design based on few-mode fibers (FMFs) which can support 4 linear polarization (LP) modes. We first present a FMF whose core is dually assisted by a nano-hole (NH) and a high-index-ring (HIR), and then substitute the dual assistance by an innovative graded concave HIR (GC-HIR) assisted structure. Using the finite element method (FEM), the parameters of the NH-HIR and GC-HIR optical fiber are adjusted to investigate their respective minimum effective refractive index difference ($\min\Delta n_{eff}$), which is $2.012 \times 10^{-3}$ for the former, and $2.532 \times 10^{-3}$ for the latter. Both optical fibers have a significant improvement on the crosstalk suppression effect, and the GC-HIR optical fiber is even better. The proposed GC-HIR FMF with special refractive index profile has potential application prospects in mode division multiplexing (MDM) optical fiber communication system, and can provide theoretical foundation for the design and analysis of subsequent optical fibers and key components.

Index Terms: Effective refractive index difference, inter-mode crosstalk, mode division multiplexing, special refractive index profile.

1. Introduction

With the development of optical fiber communication, multiplexing technology is widely used to improve communication capacity. However, due to the inherent nonlinear effect of single mode fiber (SMF), the system capacity is approaching the Shannon limit, thus traditional SMF no longer meet the development demand [1]. In order to solve the problem of insufficient system capacity, few-mode fiber (FMF) has become a research hotspot [2]–[5], and is considered one of the most straightforward optical fiber implementations for the short-reach space division multiplexing transmission system [6]–[9]. In general, FMFs have a simple structure that is easy to integrate...
[10]–[11], and need not to worry about the inter-core crosstalk as in multi-core fibers. However, inter-mode crosstalk in FMFs is a majority factor that can affect the communication quality.

As a solution to the inter-mode crosstalk, multiple input multiple output digital signal processing (MIMO-DSP) is a commonly adopted method, but with the increase of the mode number, the complexity and power consumption of the transmission system would increase greatly [12]–[14]. Another solution is to increase the effective refractive index difference (Δn eff) between adjacent modes through optical fiber design, which promotes the development of a variety of new optical fiber structures. Δn eff in cores is mainly related to the core refractive index (RI) profile, and relevant research shows that Δn eff ≥10−3 [15] can effectively reduce the inter-mode coupling. For instance, Y. Xie et al. proposed an optical fiber featuring a nanopore-assisted step-index core with double-cladding structure, achieving a minΔn eff of 1.8 × 10−3 [16]; S. Jiang et al. designed and fabricated a ring-assisted four-mode optical fiber with minΔn eff of 1.8 × 10−3 [17]. R. M. Alexander et al. proposed an optical fiber of a depressed core and four high-index side holes, which increased the minΔn eff of 4 modes from 0.8 × 10−3 to 1.2 × 10−3 without significantly affecting other characteristics [18].

In this paper, we first present a FMF which can support 4 linear polarization (LP) modes and whose core is dually assisted by a nano-hole (NH) and a high-index-ring (HIR), and then substitute the dual assistance by an innovative graded concave HIR (GC-HIR) assisted structure. Using the finite element method (FEM), the parameters of the NH-HIR and GC-HIR optical fiber are adjusted to investigate their respective minΔn eff. Calculation shows that both optical fibers have a significant improvement on the minΔn eff, and the latter has an even larger value, thus achieving a better crosstalk suppression effect. The two proposed FMFs, especially the GC-HIR optical fiber, has the characteristics of supporting multiple modes and simple preparation, which can effectively solve the problem of inter-mode crosstalk in mode division multiplexing (MDM) systems, demonstrating an important application value in high-speed and large-capacity optical fiber communication system.

2. Structural Design of Proposed Optical Fibers

According to the coupled mode theory, a large Δn eff between adjacent modes help suppress inter-mode crosstalk [19], [20]. Considering the current implementation of the reported works, we first come up with a dually assisted NH-HIR optical fiber by combining together the nano-hole and the high-index-ring. The nano-hole assistance is to penetrate a nano-scale air-hole through the core of the step-index optical fiber, whose low RI can fully reduce the n eff of LP02 without significantly influencing other modes. The ring assistance is to add a high-index-ring at a position where the power of the LP02 mode is the lowest, thus its overlapping integral with LP02 is small while that with LP21 mode large. The parameters of this NH-HIR optical fiber will be adjusted to investigate its minΔn eff to confirm the effect of the dual assistance.

Based on the parameter adjustment result in the first step, the NH-HIR dual assistance will be further substituted by a graded concave HIR assisted structure. A step-index FMF with the same core radius and relative RI difference Δn will be used as the basis for GC-HIR design. Within the fiber core of the step-index FMF, a special ring of circularly symmetrical graded RI distribution is introduced. For this ring, its RI value increases gradually along the ring radius, forming a radiation RI distribution. The ring edge has the highest RI, whose function is similar to that of the high-index-ring in the NH-HIR optical fiber structure; the ring center has the lowest RI (still higher than that of the cladding), whose function is similar to that of the nano-hole. By resorting to a graded RI distribution assistance within the fiber core, similar crosstalk suppression effect is achieved, or even better.

Fig. 1 illustrates the transverse cross-section and RI distribution of the conceived NH-HIR optical fiber (a) and GC-HIR optical fiber (b). For the NH-HIR optical fiber, the cladding was made of pure silica with RI n 2 = 1.444; the core with a radius a = 7.5 μm was made of Ge-doped silica, whose RI n 1 = 1.4537; the RI of high-index-ring is n ring; considering the preparation process, the fiber cladding diameter D was designed to be 125 μm, consistent with a standard SMF; the relative RI difference of the unassisted part is Δn = (n 1 2 - n 2 2) / 2n 2 2 = 0.67% and that of the HIR is Δn ring = (n ring 2 - n 2 2) / 2n 2 2 - Δn = 0.2%; the radius of the nano-hole was indicated by R hole,
the inner diameter and width of the HIR by $R_{\text{ring}}$ and $W_{\text{ring}}$, respectively. The HIR of circularly symmetrical graded RI distribution in the GC-HIR optical fiber was made of Ge-doped silica of different doping concentration, and its initial radius $b$ is determined by $R_{\text{ring}}$ and $W_{\text{ring}}$ of the NH-HIR structure, namely, $b = R_{\text{ring}} + W_{\text{ring}}$. The highest doping concentration at the ring edge is indicated by $P_1$, and the lowest at the ring center by $P_2$. The RI of the Ge-doped silica can be given by the following composite Sellmeier equation \[21\]:
\[
n = \sqrt{1 + \sum_{i=1}^{3} \frac{(SA_i + P(GA_i - SA_i))\lambda^2}{\lambda^2 - (SI_i + P(GL_i - SI_i))^2}}
\]
where $SA$, $SI$, $GA$, $GL$ are the coefficients of Sellmeier equation of $SiO_2$ and $GeO_2$, respectively, and $P$ is the mole percentage of $GeO_2$, here representing the doping concentration of core part without assistance.

3. Parameter Optimization

In order to investigate the min $\Delta n_{\text{eff}}$, the parameters of NH-HIR optical fiber are optimized using FEM and further applied to designing the GC-HIR optical fiber. Fig. 2 shows the respective influence of $R_{\text{ring}}$, $W_{\text{ring}}$ and $R_{\text{hole}}$ on the modal $n_{\text{eff}}$ (the left column) and $\Delta n_{\text{eff}}$ (the right column) at the wavelength of 1550 nm with $\Delta n_{\text{eff}} = 0.2\%$. First, the evolution of $n_{\text{eff}}$ with the change of $R_{\text{hole}}$ from 0.1 $\mu m$ to 0.5 $\mu m$ is presented by Fig. 2(a). We can see that the introduction of nano-hole hardly affects the $n_{\text{eff}}$ of $LP_{01}$ and $LP_{02}$. However, compared with the former, the latter has a relatively
more obvious curvature. The corresponding change of $\Delta n_{\text{eff}}$ with the increase of $R_{\text{hole}}$ is shown by Fig. 2(b). It can be found that the $R_{\text{hole}}$ size has a significant effect on the $\Delta n_{\text{eff}}$ between LP$_{21}$ and LP$_{02}$ and that between LP$_{01}$ and LP$_{11}$, where the former exhibits a great increase while the latter an obvious drop. When $R_{\text{hole}} = 0.15 \ \mu\text{m}$, the two $\Delta n_{\text{eff}}$ curves intersect, indicating a well-balanced modal $\text{min} \Delta n_{\text{eff}}$. Similarly, by respectively investigating the variation of $\Delta n_{\text{eff}}$ with the change of $R_{\text{ring}}$ and $W_{\text{ring}}$, the following values were obtained: $R_{\text{ring}} = 3 \ \mu\text{m}$, and $W_{\text{ring}} = 1.9 \ \mu\text{m}$. In sum, when $R_{\text{hole}} = 0.15 \ \mu\text{m}$, $R_{\text{ring}} = 3 \ \mu\text{m}$ and $W_{\text{ring}} = 1.9 \ \mu\text{m}$, the inter-mode $\Delta n_{\text{eff}}$ of the NH-HIR optical fiber has the minimal value. Consequently, the initial value of the ring radius $b$ in the GC-HIR optical fiber is set to be $b = R_{\text{ring}} + W_{\text{ring}} = 4.9 \ \mu\text{m}$.
Based on the adjusted parameters of the NH-HIR optical fiber, the initial parameters of the GC-HIR optical fiber are preliminarily set, and further adjusted to investigate the $\Delta n_{\text{eff}}$. The change curve of $n_{\text{eff}}$ with $b$ varying around its initial value $4.9 \mu m$ (4.5 $\sim$ 5.5 $\mu m$) is shown in Fig. 3(a). We can see that the gap between the $n_{\text{eff}}$ of LP$_{21}$ and LP$_{02}$ gradually enlarges and the gap between the $n_{\text{eff}}$ of LP$_{01}$ and LP$_{11}$ gradually shrinks with the increase of $b$ from 4.5 to 5.5 $\mu m$. The corresponding change of $\Delta n_{\text{eff}}$ with $b$ is shown by Fig. 3(b). It is clear that the radius of GC-HIR part $b$ has a significant effect on the $\Delta n_{\text{eff}}$ between LP$_{21}$ and LP$_{02}$ and between LP$_{01}$ and LP$_{11}$. When $b = 5$ $\mu m$, a well-balanced inter-mode $\min \Delta n_{\text{eff}}$ was achieved. The influence of the doping concentration $P_1$ and $P_2$ on $n_{\text{eff}}$ and $\Delta n_{\text{eff}}$ is respectively evaluated, as shown by Fig. 3(c) to Fig. 3(f). As a
result, the following final values were obtained: $P_1 = 0.132$, and $P_2 = 0.061$. According to the aforementioned composite Sellmeier equation, the core refractive index is 1.4637 and 1.4532, and the corresponding core-cladding relative refractive index difference is 1.364% and 0.637%, respectively. In sum, when $b = 5 \mu m$, $P_1 = 0.132$ and $P_2 = 0.061$, the inter-mode $\Delta n_{\text{eff}}$ of the GC-HIR optical fiber has the minimal value.

4. Performance of GC-HIR Optical Fiber

4.1 Advantage in Inter-mode Crosstalk Suppression

In order to highlight the advantages of our proposed GC-HIR structure, the inter-mode $\Delta n_{\text{eff}}$ of step-index optical fiber, NH assisted optical fiber, HIR assisted optical fiber, GC-HIR optical fiber, and the NH-HIR optical fiber is respectively investigated, as presented by Fig. 4. For all these
TABLE 1
Comparison Between Several Structures with the Same Core Diameter

| Cross-section | RI profile | Min Δn<sub>eff</sub> |
|---------------|------------|----------------------|
| Step-index    |            | 0.8 × 10<sup>-3</sup>|
| NH assisted   |            | 1.403 × 10<sup>-3</sup>|
| HIR assisted  |            | 1.485 × 10<sup>-3</sup>|
| NH-HIR        |            | 2.012 × 10<sup>-3</sup>|
| GC-HIR        |            | 2.532 × 10<sup>-3</sup>|

optical fibers of different structure with the same core radius (a = 7.5 μm), except the min Δn<sub>eff</sub>, their RI distribution profiles and corresponding cross-section diagrams are demonstrated as well in Table 1.

From the comparison, we can see that the min Δn<sub>eff</sub> of ordinary step-index optical fiber is 0.8 × 10<sup>-3</sup>, which is only 10<sup>-4</sup> orders of magnitude. The min Δn<sub>eff</sub> between adjacent modes with only NH assisted or HIR assisted structure is about 1.4 × 10<sup>-3</sup>. The proposed NH-HIR dually assisted structure increases its min Δn<sub>eff</sub> to 2.012 × 10<sup>-3</sup>, 2.5 times than that of the original step-index optical fiber, which greatly helps inhibit the inter-mode crosstalk. Finally, the innovatively proposed GC-HIR optical fiber achieves the largest inter-mode min Δn<sub>eff</sub>, that is, 2.532 × 10<sup>-3</sup>, proving its better performance in crosstalk suppression. Therefore, by introducing the GC-HIR assisted structure into the core design, the inter-mode crosstalk has been greatly reduced. Without increasing the MIMO complexity, just the fiber core design has already met the requirement of low modal crosstalk, and all supported modes can be used as different transmission channels more easily.

4.2 Other Performance Investigation of the GC-HIR Optical Fiber

The electric field distribution diagrams of each mode supported by the GC-HIR optical fiber is shown in Fig. 5. Due to the special RI distribution of the core, LP<sub>01</sub> and LP<sub>02</sub> are significantly influenced by the low RI part, while other modes are almost unaffected. We further investigate the wavelength dependence of some important performance indices at C+L band. Table 2 presents the structural parameters of the proposed GC-HIR optical fiber and related performance indices.

A<sub>eff</sub> is defined by a quantitative measurement of the transverse area occupied by a mode in the waveguide or optical fiber. The calculation results show that the smallest A<sub>eff</sub> is greater than 40 μm<sup>2</sup>, thus the high-order mode would have an even larger A<sub>eff</sub>, and would not have to worry about excessive nonlinear effects.

Calculation shows that the dispersion of the 4 LP modes within the entire C+L band is at the range of 0 to 20, which is equivalent to that of a standard SMF (17 ps/nm/km in the ITU-T).

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Therefore, the GC-HIR optical fiber proposed here can be applied to short-distance large-capacity optical networks.

DMD directly affects the complexity of MIMO signal processing [22], [23], which is defined as the group delay difference between the higher-order mode LP_{mn} and the fundamental mode LP_{01}. For the GC-HIR optical fiber, the DMD increases slightly from short wavelength to long wavelength, and its broadband characteristics meet the requirements of working at the C+L band.

**Fig. 5.** Mode field distributions of 4 LP modes in the GC-HIR at 1550 nm. (a) LP_{01}, (b) LP_{11}, (c) LP_{21}, (d) LP_{02}.

**TABLE 3**

Comparison With Similar FMFs Released Recently

|                     | Core Overall Size | Core RI  | LP Mode Number | Min Δn eff for LP Mode |
|---------------------|-------------------|----------|----------------|-----------------------|
| Ring-core FMF[24]   | 7.3 µm (ring-core outer radius) | 1.4590 | 5              | 0.80 × 10^5           |
|                     | 3.5 µm (ring-core thickness) |         |                |                       |
|                     | 7.5 µm             |         |                |                       |
| Octagonal-arrayed   | 3.5 µm (ring-core outer radius) | 1.4537 | 4              | 1.0 × 10^5            |
| cladding-rod-assisted DC RC-FMF[25] | 3.5 µm (ring-core thickness) |         |                |                       |
|                     | 2.2 µm (rod radius) |         |                |                       |
|                     | 8 µm               |         |                |                       |
| CA DMFSH RC-FMF[26] | 5.5 µm (ring-core outer radius) | 1.4570 | 5              | 1.01 × 10^5           |
|                     | 5.5 µm (ring-core thickness) |         |                |                       |
| NH-HIR              | 5.8 µm (side hole radius) | 1.4566  | 4              | 2.012 × 10^3          |
|                     | 7.5 µm (core radius) | (core:1.4537) |                |                       |
| GC-HIR              | 7.5 µm (core radius) | (highest RI:1.4637) | 4              | 2.532 × 10^3          |
|                     |                    | (lowest RI:1.4532) |                |                       |
4.3 Comparison With FMFs Released Recently

The characteristics of the two optical fibers designed in this paper (the NH-HIR and the GC-HIR optical fibers) are compared with other similar FMFs recently released, as shown by Table 3. From the comparison, we can see that our two optical fiber designs can achieve a larger $\min \Delta n_{\text{eff}}$, and the crosstalk between adjacent modes are better suppressed. Both of these two designs, especially the novel the GC-HIR optical fiber, meet the transmission requirements of the high-speed and large-capacity MDM system, and provide theoretical foundation for the design and analysis of subsequent optical fibers and key components.

5. Conclusion

In this paper, a FMF with its core dually assisted by a nano-hole and a high-index-ring is designed, which works as the initial parameter supplier and contrast reference for the later proposed GC-HIR optical fiber. By replacing the dual assistance by the graded concave HIR structure, the $\min \Delta n_{\text{eff}}$ between adjacent modes can reach $2.532 \times 10^{-3}$, achieving an even better inter-mode crosstalk suppression. Furthermore, the mode field distribution of the GC-HIR optical fiber is simulated, and main performance indices, including $n_{\text{eff}}$, $\Delta n_{\text{eff}}$, $A_{\text{eff}}$, DMD and loss of each mode, are also analyzed over the whole C+L bands. The proposed GC-HIR FMF can effectively solve the problem of inter-mode crosstalk in high-speed large-capacity MDM system, demonstrating important application value, and can provide theoretical foundation for the design and analysis of subsequent optical fibers and key components.

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