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Design of compact multi-ring-core few-mode fiber for dense space-division multiplexing in C+L band

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Abstract: We design a compact 37-ring-core fiber, each core can support 5 mode groups in C+L band. The theoretical inter-core crosstalk keeps lower than -50 dB/km when the bending radius is larger than 7 cm.

1. Introduction

The high growth rate of the demand of communication capacity requires new types of optical fiber to construct the next generation information highway. Space-division multiplexing (SDM) in optical fiber has been proposed as an effective solution of capacity crunch [1]. In the recent decade, orbital angular momentum (OAM) of light has been demonstrated as a useful degree of freedom for SDM [2,3]. In few-mode fibers, compared with linearly polarized (LP) modes, OAM modes have the advantage of circular symmetrical modal profile, which reduces the design complexity of many optical components like fiber amplifier, multiplexer and demultiplexer. In addition, multi-core fiber can further increase the data transmission capacity [4]. Therefore, multi-core few-mode fibers (MC-FMFs) are ideal media for achieving dense SDM [5]. However, the inter-core crosstalk (XT^c) restricts the mode number of MC-FMFs, the state-of-the-art record is a 38-core 3-mode fiber supporting 228 SDM channels [6].

In this paper, we proposed and optimized a heterogeneous 37-ring-core 5-OAM-mode-group fiber in C+L band (1.53 to 1.625 μm), which has ultra-low XT^c and compact core arrangement. The calculated XT^c is lower than -50 dB/km when the fiber bending radius is beyond 7 cm. Theoretically, the designed fiber can provide 666 mode channels for a 4×4 multiple-input multi-output (MIMO) signal processing assisted SDM system.

2. Design and optimization of trench-assisted ring core

Eigenmodes of optical fiber can be classified into $HE_{v,l}$, $EH_{v,l}$ $TE_{0,l}$ and $TM_{0,l}$ modes, where v and l ($= 1,2,3\cdots\cdots$) represent azimuthal order and radial order of modes, respectively. Ring-core fiber has an annular high-index profile, which can suppress radial higher-order modes ($l > 1$) without damaging the azimuthal higher-order modes ($v > 1$) [7]. This property can be used for designing fibers only supporting donut-shape OAM modes. The superposition of two orthogonal polarization states of each HE and EH mode with a $\pm\pi/2$ phase difference can form OAM modes as [8]

$$\mathrm{OAM}^{\pm}_{\pm(v-1),l} = \mathrm{HE}^{\mathrm{e}}_{v,l} \pm i\mathrm{HE}^{\mathrm{o}}_{v,l}, \tag{1a}$$

$$\mathrm{OAM}^{\mp}_{\pm(v+1),l} = \mathrm{EH}^{\mathrm{e}}_{v,l} \pm i\mathrm{EH}^{\mathrm{o}}_{v,l}, \tag{1b}$$

where "e" and "o" represent even and odd polarization distributions, the superscripts "+" and "−" correspond to left- and right-hand circular polarization, respectively. The fiber index profile is shown in Fig. 1(a). The ideal size of ring core for guiding a certain number of OAM mode group can be tuned by changing the central index (n_{ce}) and the core index (n_{co}). Figure 1(b) shows the design regions for guiding 5 OAM mode groups in C+L band. The outer radius of ring core (r_2) decreases with the increase of core doping ratio ($\Delta_{co} = (n_{co} - n_{cl})/n_{co}$) which is beneficial to the compact design of multi-ring-core fiber. In addition, the negative doped central area ($\Delta_{ce} = (n_{ce} - n_{cl})/n_{ce}$) can make the first radial higher-order mode group ($OAM_{0,2}$) become cutoff when the value of r_1/r_2 is relatively low. Hence, the available width of ring core can be enlarged. Although reducing the core size is beneficial to the compactness of multi-ring-core fiber, we should make sure the high purity of OAM modes in the condition of large Δ_{co}. We choose the points in the regions of different Δ_{co} as noted by white circles in Fig. 1(b) and then illustrate the purity of OAM modes in Fig. 1(c). The mode purity decreases with the increase of Δ_{co}. The fundamental modes have the worst mode purity of 99.924% when $\Delta_{co} = 1.76\%$. These results indicate that the OAM modes can keep relative high mode purity when Δ_{co} is lower than 1.76%.

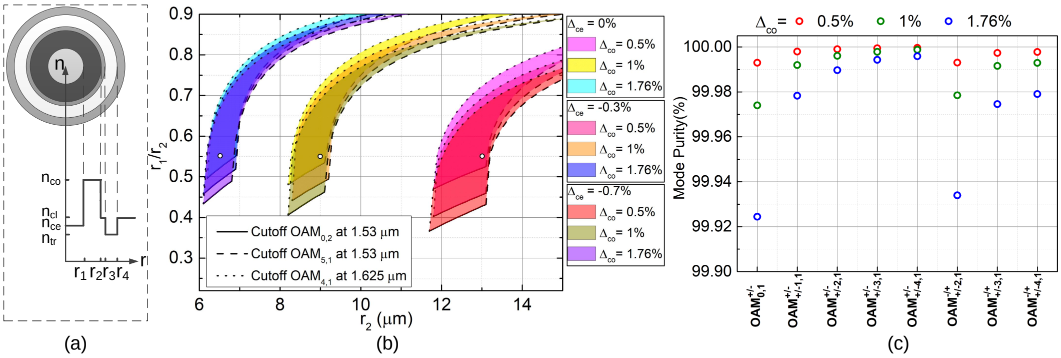

Fig. 1. (a) The index profile of trench-assisted ring-core fiber, (b) the design regions for supporting 5 OAM mode groups in C+L band, (c) the OAM mode purity in the condition of different Δ_{co}

The position and width of the trench is important for reducing the XT^c [9]. In Fig. 2(a), we show the variation of the maximum XT^c when $\Delta_{co} = 1\%$, $\Delta_{ce} = 0\%$, $\Delta_{tr} = -0.7\%$ and the core-to-core gap is 40 μm. It can be seen that the increase of the width of trench can rapidly reduce the XT^c, and the gap between core and trench also helps to decrease the XT^c.

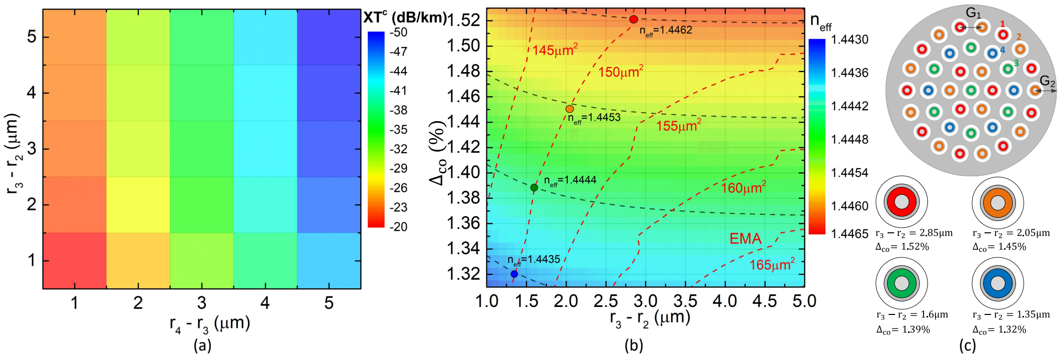

Fig. 2. (a) The variation of XT^c versus the core-trench gap $(r_3 - r_2)$ and the trench width $(r_4 - r_3)$ when the core-to-core gap is 40 μm at the wavelength of 1.55 μm, (b) the n_{eff} and EMA of OAM$_{\pm4,1}$ versus Δ_{co} and $r_3 - r_2$ at the wavelength of 1.625 μm, (c) the core parameters and arrangement of the heterogeneous 37-ring-core fiber

Another way to reduce XT^c is using heterogeneous cores. We adopt that $r_1 = 4$ μm, $r_2 = 7.3$ μm, $r_4 - r_3 = 5$ μm, $\Delta_{ce} = -0.4\%$ and $\Delta_{tr} = -0.7\%$ to design 4 types of heterogeneous ring cores. The n_{eff} and effective mode area (EMA) of modes in different cores can be adjusted by changing Δ_{co} and $r_3 - r_2$. The four kinds of ring cores are noted by circle in Fig. 2(b) and the specific parameters of each core are illustrated in Fig. 2(c). The Δn_{eff} of OAM$_{\pm4,1}$ in each couple of heterogeneous cores is larger than 9×10^{-4}, and the EMAs are approximately equal to 150 μm^2. The big Δn_{eff} helps to reduce XT^c, and the similar EMAs of modes can decrease the loss of fiber splice.

3. Crosstalk analysis

The calculation of the XT^c follows the analytical formula reported in Ref. [10]. The effect of micro-deviations of two adjacent cores is considered by using an exponential perturbation autocorrelation function with a correlation length of 10 mm. The effect of fiber twisting is averaged in a twisting period. The XT^c between core 3 and core 4 in a straight fiber at the wavelength of 1.625μm, when the core-to-core gap (G_1) is 35 μm, is shown in Fig. 4(a). We find that the highest order OAM mode group suffers the largest XT^c, this trend can be applied to any two adjacent cores. Therefore, we use the XT^c between OAM$^+_{+4,1}$ and OAM$^+_{-4,1}$ to represent the maximum XT^c. The bending properties of the maximum XT^c is shown in Fig. 4(b). The XT^c peaks move to smaller bending radius with the increase Δn_{eff}. Thanks to the design of heterogeneous cores, the peak bending radius is smaller than 7 cm. Therefore, the designed fiber is bending insensitive when the bending radius is larger than 7 cm, and the XT^{c} keeps lower than -50 dB/km. The gap between the outer most ring core and the cladding boundary (G_2) is 40 μm to avoid the excess loss caused by the high index coating layer. Consequently, the cladding diameter of the designed fiber is 290 μm, which is more compact than the fiber proposed in Ref. [6], moreover, the amount of guided modes increases to 666.

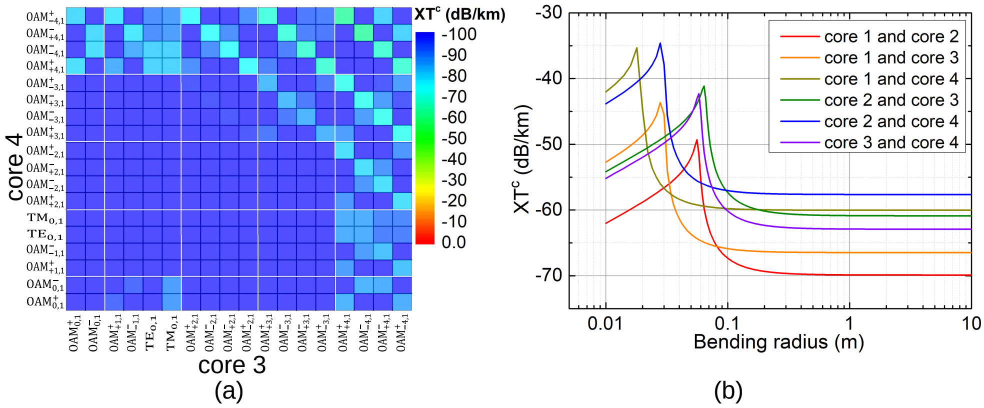

Fig. 3. (a) XT^{c} of all modes between core 3 and core 4 at the wavelength of 1.625 μm, (b) bending property of the XT^{c} between $\mathrm{OAM}^{+}_{+4,1}$ and $\mathrm{OAM}^{+}_{-4,1}$ in any two adjacent cores

4. Conclusion

We proposed an optimized design of 37-ring-core 5-OAM-mode-group fiber for SDM in C+L band. The XT^{c} remains lower than -50 dB/km when the bending radius is larger than 7 cm. The compact core arrangement is achieved with a cladding diameter of 290 μm. Theoretically, the designed fiber can provide 666 SDM channels.

5. Acknowledgments

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