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Low crosstalk six-core five-mode fiber with high refractive index rings and air trench

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Abstract

A novel six-core five-mode fiber composed of an air trench and high refractive index ring is proposed in this paper. Numerical analysis shows that the fiber can stably transmit five LP modes in the C + L band. The effective refractive index difference of the five LP modes at 1.55 μm is more significant than 1.4 × 10^{-3}, which is conducive to the independent transmission of the modes. The inter-core crosstalk of the fiber is less than -95 (dB / 100km). Therefore, the fiber can be well used to build a large-capacity optical fiber transmission system.

Keywords: Multi-core fiber; Crosstalk; Few-mode multi-core fiber; Air trench

1. Introduction

Due to the rapid development of big data services such as 5G, big data, cloud services, and Internet of Things technology, higher requirements are placed on the transmission capacity of optical fibers. However, the existing propagation media are constantly constrained by the Shannon limit [1]. Single-mode fiber (SMF) based on wavelength division multiplexing, polarization multiplexing, multi-level modulation, and other technologies can no longer meet the needs of large-capacity transmission. To solve the problem of information transmission capacity, spatial multiplexing (SDM) technology is used to expand the channel in the spatial dimension of the transmission medium to improve the transmission capacity. Among them, multi-core fiber [2] (MCF) based on spatial division multiplexing (SDM) and few-mode fiber [3] (FMF) based on mode division multiplexing (MDM) are commonly used SDM fibers. MCF fiber is designed to increase the number of fiber cores, and FMF is to increase the number of modes that can be transmitted in a single core. However, for MCF, due to the limitation of cladding size, the increase in core number will lead to the deterioration of inter-core crosstalk (ICXT). For FMF, the increase of transmission modes will lead to stronger inter-mode coupling, which will seriously affect the quality of information transmission.

In 2021, researchers from YanShan University proposed a 7-core 5-LP mode fiber.To achieve large-capacity long-distance transmission of SDM transmission. The mode area of the five LP modes is greater than 86μm², and the low XT is about -50 dB / km [4]. For Few-mode multi-core fiber (FM-MCF) [5], the cladding contains multiple cores, and each core can transmit multiple LP modes, which greatly increases the number of optical spatial channels. Although FM-MCF has great potential in improving the transmission capacity of optical fiber communication systems, the current FM-MCF research is still in its infancy and far from large-scale commercialization.

To reduce the excessive XT In FM-MCFs, researchers have proposed different solutions, such as the trench-assisted method [6,7], the hole-assisted method [8], and the non-uniform core structure [9]. Usually, these three methods are combined to produce better results. For example, a low crosstalk uniform seven-core five-LP mode fiber based on high and low refractive index double rings has been recently proposed, which can significantly suppress ICXT ≤ -30 (dB /100 km) and bending loss (BL) [10]. By introducing a high and low refractive index ring into the core, a low ICXT is achieved, so that the effective RI check is greater than 10^{-3}, and the relative core multiple coefficients (RCMF) is 62.17 [11].

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In this paper, a six-core five-mode FM-MCFs (AHR) assisted by air trench and high refractive index rings for large-capacity long-distance communication is proposed. The bending loss and the most critical crosstalk effects are analyzed in detail. Using COMSOL Multiphysics analysis software, the dependence of ICXT and loss on fiber geometry is calculated. The results show that the designed FMMCF can achieve a maximum mode field area of 94 um^2 and ultra-low crosstalk of -95.85 (dB / 100km) at a wavelength of 1.55 μm. In addition, the fiber RCMF reaches 42.83, indicating that there are both low ICXT and high space utilization. The new structure adopted in this paper has important reference significance for the future development of FM-MCF and may provide a new way to improve the transmission performance of the SDM system.

2. Optical fiber simulation principle

The low XT and large capacity characteristics of optical fiber are very important in remote communication systems. In this paper, the performance of FM-MCF is simulated and analyzed by COMSOL Multiphysics software.On the other hand, the inter-core XT is calculated with coupled mode theory (CMT) [12]and coupled power theory (CPT)[13]. The mode coupling coefficient between core m and n can be expressed as [4] :

$$k_{mn} = \frac{\omega\varepsilon_0 \iint_\infty (N^2 - N_n^2) E_m^* \cdot E_n dxdy}{2\iint_\infty (E_{mx}H_{my}^* - E_{my}H_{mx}^*) dxdy} \quad .... (1)$$

E and H are the electric fields and magnetic field distribution, respectively. The sign ω represents the angular frequency of the electromagnetic field, $\varepsilon 0$ represents the vacuum dielectric constant, and N is the refractive index profile of the entire optical waveguide, and Nn is the refractive index profile when only fiber core n exists., respectively.

The expression of the average power coupling coefficient in uniform MCF is given by using the modal coupling coefficient [14].

$$\bar{h}_{mn} = \frac{2K_{mn}^2 R_b}{\beta_m d} \quad .... (2)$$

R and β_m are the bending radius and modal propagation constant of core m, and d is the core pitch of adjacent fiber cores,respectively. Consequently, the cross talk between adjacent cores relating to fiber transmission length L is written as follows [14].

$$XT = 10lg\left[\tanh \bar{h}_{mn} \mathrm{L}\right] \quad .... (3)$$

The effective mode field area (Aeff) is one of the important parameters to measure the performance of FM-MCF . The calculation formula of Aeff can be expressed as [14].

$$Aeff = \frac{\left[\iint |E|^2 \, dx \, dy\right]^2}{\iint |E|^4 d_x \, dy} \quad .... (4)$$

Where |E| means electric field mode.

Table 1 Preliminary determination parameters of FM-MCF

Parameter	Value
Position of the inner ring r1	4.8 μm
Thickness of high refractive index ring w1	1.6 μm
core radius a	8.4 μm
Air-hole radius c	14.4 μm
Core pitch p	48 μm
Relative RI difference between core and cladding Δn1	0.89%
Relative RI difference between inner ring and core Δn2	0.2%
Width of inner cladding b	3.4 μm

Cladding diameter CD	150 μm

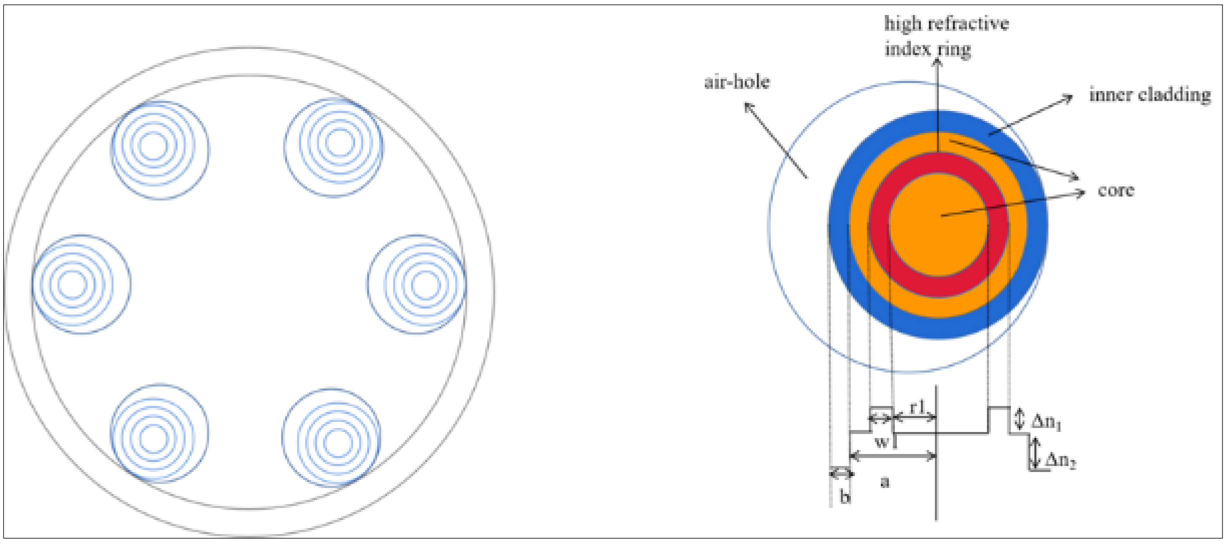

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Figure 1 (a) Schematic structure of an AHR high refractive index ring 6-core 5-LP-mode fiber. (b) Schematic diagram of the structural distribution of the few-mode unit

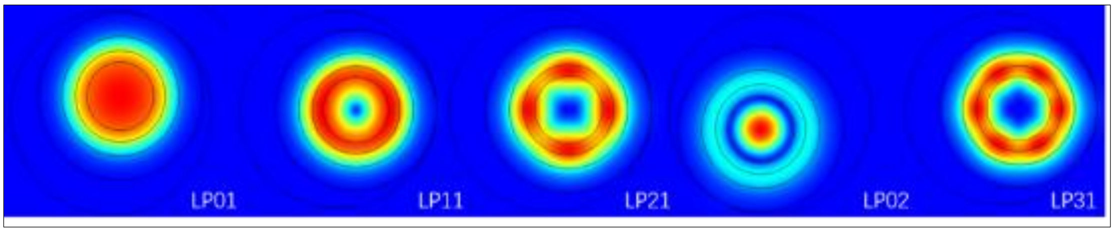

Figure 2 Electric field diagram of five modes

3. Design of the proposed FM-MCF

Common methods for reducing fiber crosstalk are trench assistance, air-hole assistance, and heterogeneous core methods. The trench can completely wrap the fiber core, but due to the limitation of the existing doping technology, the refractive index can only be reduced limitedly. In contrast, the air-hole can reach the lowest index, but the air-holes must be dispersed around the fiber core, and there is still energy leakage between the adjacent air-holes. Therefore, we adopt the method of air hole trench to reduce crosstalk. At the same time, we adopt a high refractive index ring to improve the Δneff between different modes.

In this paper, we propose a six-core five-mode FM-MCF as shown in Fig.1 (a). Each core consists of a core, a high refractive index ring, an inner cladding and crescent-shaped pores as shown in Fig.1 (b). The meaning of the symbol and the initial parameters can be viewed in Table 1. The RI values of the inner cladding and fiber cladding formed by pure quartz glass (SiO_2) can be obtained by the Sellmeier equation [15]. The RI values of the core and the high refractive index ring can be calculated according to the mathematical relationship in Table 1. Where, Δn1, Δn2 are (n1-n0) / n0, (n2-n1) / n1 (where, n0, n1, n2 are the refractive index of cladding, core and high refractive index ring, respectively. All values are set according to the actual manufacturing level, and the core parameters are given to ensure the five-level mode transmission in the C + L band.The electric field of the five modes is shown in Fig 2. The design of high refractive index can improve the effective refractive index difference of LP mode. The design of the air trench can reduce the ICXT of the fiber.

4. Performance anal ysis of the proposed FM-MCF

4.1. Analysis of Inter-core XT

During mode transfer, FM-MCF will produce inter-core XT and intra-core XT [16]. When the Δneff between modes is greater than 10^{-3}, the intra-core XT between cores will be ignored. As shown in Fig. 3, Δneff between the FM-MCF modes proposed in this paper is greater than 1.4 × 10-3, so this paper only considers the inter-core XT.

Due to the use of air trench and high refractive index rings to reduce ICXT, we will discuss the relationship between high refractive index ring w1, air hole radius c, core r1, core pitch p, and ICXT.

Firstly, we discuss whether the existence of high refractive index rings can improve the performance of ICXT. Fig.4 shows the difference of ICXT between the fiber with high refractive index ring and the fiber without high refractive index ring. It can be seen that when the wavelength is 1.55 μm, the ICXT of the fiber without high refractive index ring is about -80 (dB / 100km), and the fiber with high refractive index ring is about -95 (dB / 100km), so the high refractive index ring can effectively reduce the ICXT of the fiber, because the smallest Δneff between LP02 and LP21 easily causes XT in the first five LP modes. When there is a high refractive index ring, the Δneff between the modes will be increased, thereby effectively suppressing ICXT.

Secondly, we discuss the influence of high refractive index ring thickness W1, air hole radius c1, core radius r1 and core pitch p on ICXT. Fig.5 shows the relationship between different LP modes and ICXT at different w1. It can be seen that LP31 decreases with the increase of w1. When LP21 is w1 > = 1.6 μm, ICXT tends to be stable. However, LP01, LP11 and LP02 have an increasing trend when w1 > 1.6 μm.This is because when the fiber core size increases, the optical power is more tightly coupled with the fiber core, thereby reducing the power leakage, and resulting in a decrease in ICXT. When r1 = 4.8 μm, the minimum crosstalk values of LP21 and LP11 are less than-100 (dB / 100km). So r1 = 4.8 μm.The relationship between the thickness of the high refractive index ring and the crosstalk is shown in Fig.5 (b). it can be seen that the reaction of different modes of ICXT and w1 is different, and we focus on the LP31 mode, roughly with the increase of w1, ICXT decreased, however, LP21, LP11 mode in w1 = 1.6μm ICXT minimum, so w1 = 1.6 μm.

In FM-MCFs, the distance between cores should be as short as possible to accommodate more cores in a limited cladding area. However, when the core pitch decreases, the requirement for fiber diameter will be limited due to the sharp deterioration of ICXT. Therefore, the core pitch must be optimized while ensuring the transmission quality. As shown in the Fig.6 (a), the crosstalk of each mode between adjacent cores is obtained by scanning the core pitch from 38 μm to 50 μm. The results show that ICXT decreases with the increase of core pitch. Combined with the results of bending loss, the above optimization results make the core pitch of the proposed fiber 48 μm.

The air trench method is used to suppress ICXT in the fiber, therefore, the relationship between ICXT and pore size was studied, as shown in the Fig.6 (b). We can see that compared with the ICXT of LP31 and LP21 modes, the ICXT of LP01, LP11 and LP02 modes is generally lower than −140 (dB / 100 km). However, when the pore size increases to more than 14.8μm, the fiber crosstalk is as low as-100 (dB / 100km). The overall trend follows the rule that the larger the air-hole, the smaller the ICXT.Considering the bending loss, the air hole radius c is selected as 14.4 μm.

Due to the use of air trench and high refractive index rings to reduce ICXT, we will discuss the relationship between high refractive index ring w1, air hole radius c, core r1, core pitch p, and ICXT.

Fig.3 shows that the existence of high refractive index rings can effectively reduce ICXT, because the existence of high refractive index rings can improve the refractive index difference between different modes. It is well known that among the first five LP modes, the smallest Δneff between LP21 and LP02 easily causes mode XT. When the overlap integral between the inner ring and LP02 mode is small, and the overlap integral between the inner ring and LP21 mode is large, the effective RI of LP21 mode will increase, while the effective RI of LP02 mode is basically unchanged. Therefore, the larger Δneff between LP21 and LP02 can effectively suppress the mode coupling. The inner cladding is retained to enhance the optical confinement ability of the fiber core. The outer ring around the core can effectively prevent the leakage of core energy and avoid the influence of optical signals from other cores.

The ICXT curves of the five LP modes with the fiber core radius r1 are shown in Fig.4 (a). This is because when the fiber core size increases, the optical power is more tightly coupled with the fiber core, thereby reducing the power leakage, and resulting in a decrease in ICXT. When r1 = 4.8 μm, the minimum crosstalk values of LP21 and LP11 are less than-100 (dB / 100km). So r1 = 4.8 μm.The relationship between the thickness of the high refractive index ring and the crosstalk is shown in Fig.4 (b). it can be seen that the reaction of different modes of ICXT and w1 is different, and we focus on the LP31 mode, roughly with the increase of w1, ICXT decreased, however, LP21, LP11 mode in w1 = 1.6μm ICXT minimum, so w1 = 1.6 μm.

In FM-MCFs, the distance between cores should be as short as possible to accommodate more cores in a limited cladding area. However, when the core spacing decreases, the requirement for fiber diameter will be limited due to the sharp deterioration of ICXT. Therefore, the core spacing must be optimized while ensuring the transmission quality. As shown in Fig.6 (a), the crosstalk between adjacent cores is obtained by scanning the core spacing from 38μm to 50μm. The results show that ICXT decreases with the increase of core spacing. Combined with the bending loss results in Fig.6 (b), the above optimization results make the core spacing of the proposed fiber 48 μm.

Because of the use of air hole trenches to suppress ICXT in optical fibers, we studied the relationship between ICXT and air hole radius, as shown in Fig.7. It can be seen that the air hole radius has little effect on the ICXT of LP11, LP21 and LP02 when the air hole radius is 14-14.9μm.However, LP01 and LP31 decrease with the increase of air hole. When the air hole radius is greater than 14.4μm, the ICXT of LP31 is less than -80 (dB / 100km).

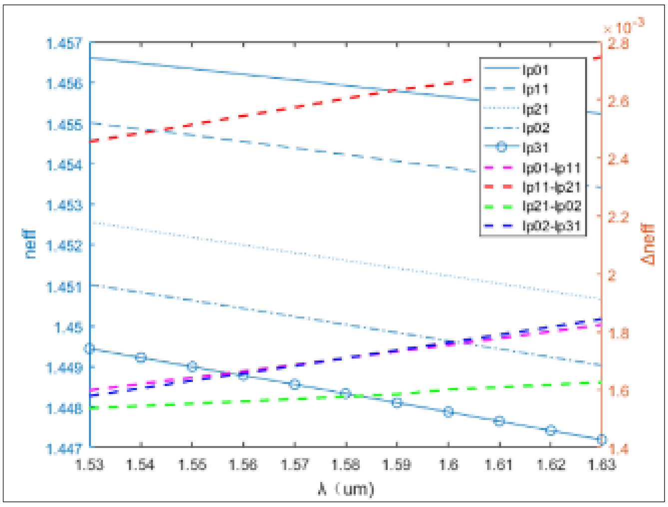

Figure 3 The effective refractive index and effective refractive index difference of five LP modes

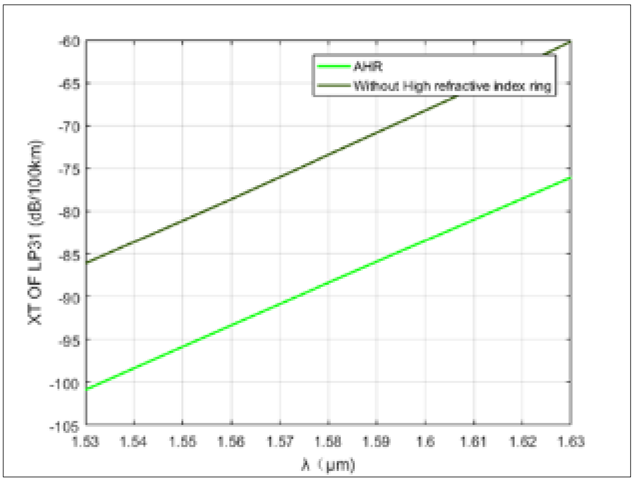

Figure 4 The effect of high refractive index ring on ICXT

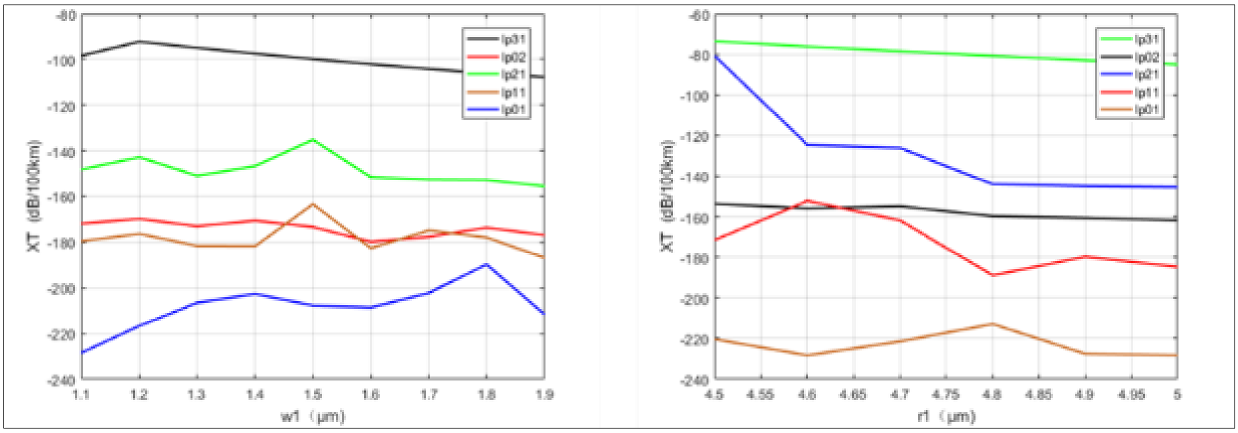

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Figure 5 The relationship between ICXT of five LP modes and (a) core radius r1 and (b) high refractive index ring thickness w1

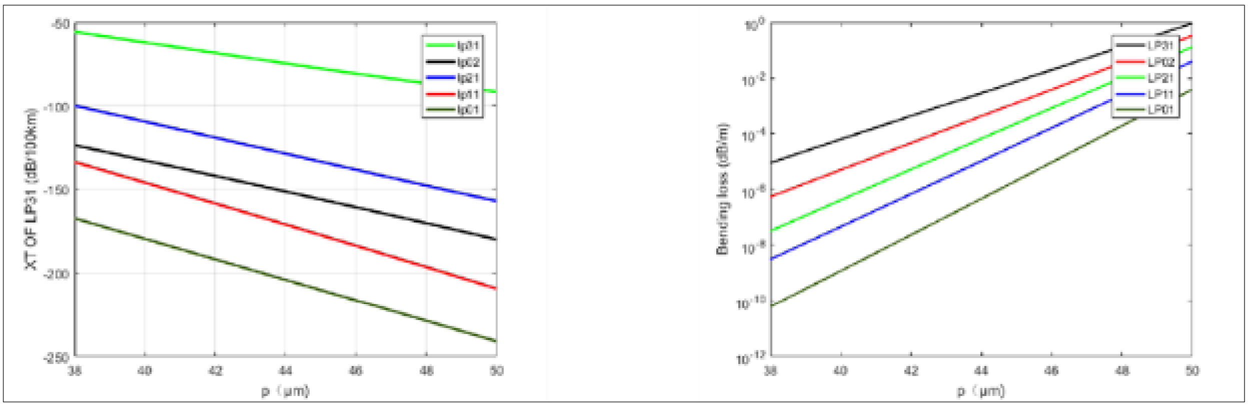

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Figure 6 The effect of core pitch p on different modes of ICXT and BL

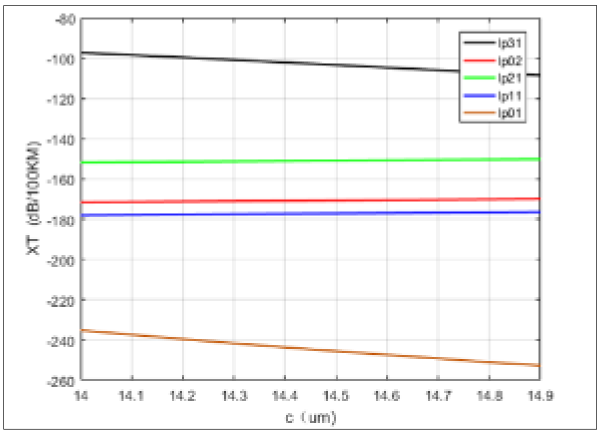

Figure 7 The relationship between air hole radius c and ICXT

4.2. Bending loss

Bending loss (BL) is an important index of modal transmission. When the mode BL is too large, it will not meet the requirements of long-distance stable transmission. In our model, the bent fiber is converted into a straight fiber by the equivalent RI method, and its equivalent RI profile is[16]

$$n_{eq} = n_{material}\left(1 + \frac{x}{1.28\mathrm{Rb}}\right) \quad ………(5)$$

Where $n_{material}$ the refractive index of the original material of the fiber is represented, and Rb is the bending radius. By designing the structure, the influence of BL in the transmission process can be reduced. BL can be easily estimated as [16]

$$BL = \frac{40\pi}{ln(10)\lambda} imag(neff) \quad ………(6)$$

where *imag (neff)* is the imaginary part of mode neff. The symbol λ represents the operating wavelength.

In this study, we use a high refractive index ring design to reduce the bending loss. It can be seen from Fig.8 (a) that the existence of high refractive index ring can reduce the bending loss to a certain extent, while Fig.8 (b) shows the relationship between the bending loss of different modes and the thickness w1 of high refractive index ring.

It can be seen from Fig.9 (a) that the bending loss increases with the increase of radius c. Similarly, Fig.9 (b) shows that the increase of core distance p also leads to the increase of bending loss. Considering that XT decreases with the increase of p, it is best to choose the core spacing P of 48 μm and the pore radius c of 14.4 μm.

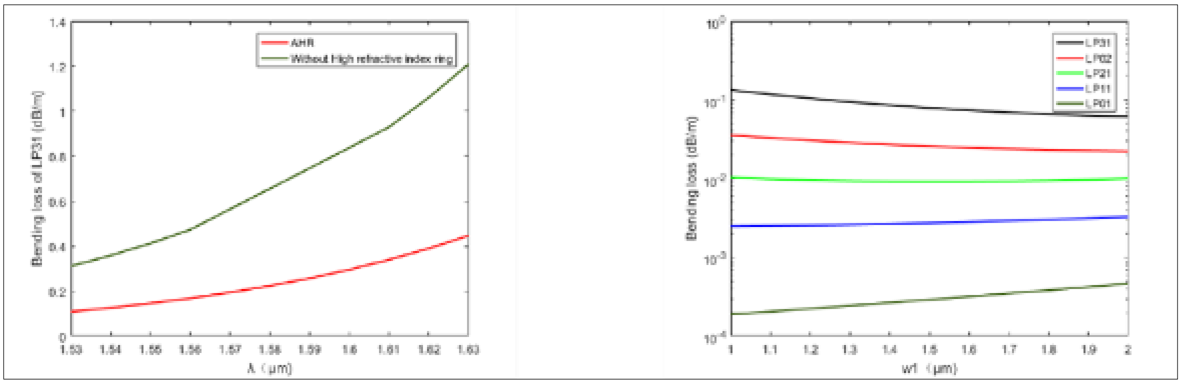

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Figure 8 (a) The effect of high refractive ring on bending loss and (b) the bending loss of different modes in C + L band

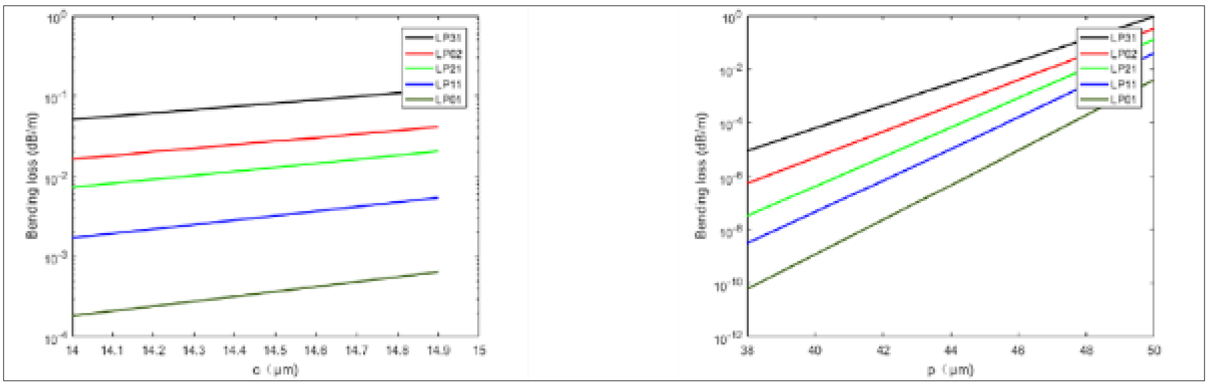

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Figure 9 The relationship between BL of five LP modes and (a) air hole radius c and (b) core pitch p

4.3. Mode Effective Refractive Index And Aeff

Larger Aeff can effectively reduce the nonlinear effect, but excessive Aeff will lead to inter-core energy overflow, increase inter-core crosstalk and fiber bending loss. The effective refractive index difference of each mode in the core should be as large as possible. If Δneff is too small, it will cause serious inter-mode crosstalk. The effective mode area increases with the increase of the core radius, and the effective refractive index difference of each mode decreases with the increase of the core radius. Therefore, it needs to be considered comprehensively.

Fig.10 shows the effective mode area of different modes in the C + L band, which increases with the increase of wavelength. It can be seen that the effective mode area of the FM-MCF designed in this paper is greater than 90 μm^2.

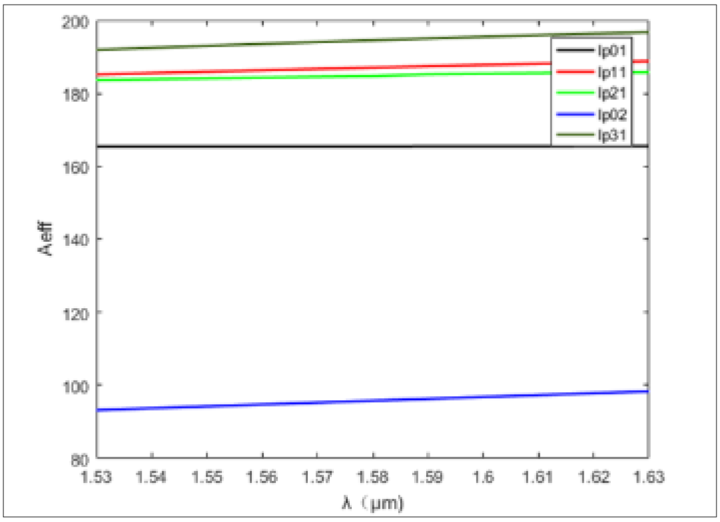

Figure 10 The relationship between Aeff and wavelength in different modes

4.4. Relative Core Multiplexing Factor

The core density of MCFs is characterized by CMF, which can be expressed by[18]

$$CMF = \frac{N_{core}\sum Aeff}{\pi(D/2)^2} \quad \text{…………..} (7)$$

Where N_{core} is the number of fiber cores, *Aeff* is the Aeff of the transmission mode in the fiber core, and *D* is the fiber diameter. Relative CMF (RCMF), the ratio of CMF of FM-MCF to that of standard single-mode fiber, is introduced. The Aeff of standard single-core single-mode fiber (cladding diameter 125 μm) is ~ 80 μm^2 at 1550 nm. Therefore, the RCMF expression is

$$RCMF = \frac{N_{core}\sum Aeff}{\pi(D/2)^2} / \frac{80}{\pi(125/2)^2} \quad \text{………} (8)$$

After calculation, the RCMF of the six-core four-mode fiber proposed in this study is as high as 43.8, which has obvious advantages over the previously reported high-density MCF [4].

5. Summary of optimization Resul

To obtain better inter-core XT, this paper adopts the method of air trench. However, the size of the air trench is closely related to the bending loss, which will lead to the lower inter-core XT and the higher bending loss. Through calculation, it is found that the introduction of a high refractive index ring can reduce the XT between cores well. For the LP31 mode that we are most concerned about, the inter-core XT drops to − 95 (dB / 100km), and the remaining modes also decrease significantly. The ICXT of each mode after optimization is shown in Table 2. It can be seen from Table 2 that the Aeff of the five LP modes is greater than 90 μm2 after the introduction of wind trench and high refractive index ring. Therefore, we can still assume that the proposed fiber has a large mode area. In addition, the introduction of a high refractive index ring also solves the problem of low effective refractive index difference between different modes in the core.

Table 2 The best fiber performance at 1550 nm (R = 30 mm)

	Inter-core XT(dB/100 km)	**Aeff(μm^2)**	**BL of LP31 (R = 30 mm)**	**Δneff**
LP01	-229.84	165.463	0.1457(dB/100turns)	
LP11	-185.73	185.453		0.0016(LP01-LP11)
LP21	-141.51	184.008		0.0025(LP11-LP21)
LP02	-160.15	94.161		0.0016(LP21-LP02)
LP31	-95.8463	192.943		0.0017(LP02-LP31)

Table 3 summarizes several SDM fibers reported in recent years, including trench-assisted MCF, air-hole-assisted MCF or air-trench-assisted MCF, and compares our work with them in ICXT characteristics. Note that the ICXT column refers to the worst crosstalk performance in fiber transmission mode. Obviously, our proposed fiber has considerable advantages in terms of channel number and ICXT level.

Table 3 Inter-Core Cross Talk Characteristic Comparison with SDM Fibers Published

SDM Fiber	**Channels**	**ICXT**
Six-core fiber[4]	6x4	-56(dB/100km)
Seven-core fiber[19]	7x5	-79(dB/km)
Thirteen-core fiber[20]	13x4	-50(dB/km)
Thirteen-core fiber[21]	13x6	-60.5(dB/km)
Seven-core fiber[22]	7x4	-44.66(dB/100km)
Our Work	6x5	-95.85(dB/100km)

6. Conclusion

In this paper, a low crosstalk five-mode six-core AHR FM-MCF is proposed as a large-capacity communication fiber. Through the comprehensive discussion and analysis of the sensitive problems existing in the current FM-MCF technology development, namely ICXT and bending loss, the geometric parameters are optimized. The high RCMF of the fiber is 43.8, ensuring strict five-mode transmission in the core. For all transmission modes, the ultra-low crosstalk is −95.85 (dB / 100 km). This work provides a new way for the future development of large-capacity remote transmission.

Compliance with ethical standards

Disclosure of conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

The authors are unable or have chosen not to specify which data.

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