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Mode transmission performance study of a novel heterogeneous helical cladding fiber with an isolation ring

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Abstract

Large mode area (LMA) fibers are widely used in high power fiber lasers to solve the nonlinear problems. In this work, a novel structure of LMA fiber with heterogeneous helical claddings and an inner isolation ring (HHCR) designed for 2.0 μm is proposed, and coordinate transformation simulation technique is adopted to analyze the fiber mode transmission characteristics. Fiber parameters effects on mode transmission loss and bending characteristics are both analyzed in detail. For a straight fiber, the optimized fiber parameters are $\Lambda=22\sim23$ mm, $\theta=13°\sim15°$, $R_1=120$ μm, $R_2=150$ μm, n_0 (n_2)$=1.439\sim1.4392$, n_1 (n_3)$=1.437\sim1.441$, $d=2\sim4$ μm, the single mode core diameter is 60 μm and the effective mode area is 2010 μm^2. For a bent fiber, the optimized fiber parameters are $\Lambda=24$ mm, $\theta=9°\sim10°$, n_0 (n_2)$=1.439$, n_1 (n_3)$=1.438$, $R_1=120$ μm, $R_2=150$ μm, $d=2\sim5$ μm, $R=0.4\sim0.5$ m, the single mode core diameter is 64 μm and the effective mode area is 1950 μm^2. Thus, the HHCR fiber can work efficiently for LMA and single mode operation. The isolation ring can effectively reduce the fundamental mode loss and improve the output spot quality. The fiber structure is all solid and the helix pitch is long, so it is relatively easy to fabricate and use. The proposed fiber will have good applications in high-power fiber lasers.

Keywords Fiber lasers · Large mode area fiber · Heterogeneous helical cladding fiber · Mode transmission characteristics

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1 Introduction

High power fiber lasers are widely used in many fields such as national defense, medical treatment and manufacturing industry due to their many inherent merits (Limpert et al. 2002; Hideur et al. 2001). However, the increasing laser power demands larger mode area (LMA) of optical fiber to mitigate nonlinear effects (Jeong et al. 2004; Fini 2007; Song et al. 2008; Yang et al. 2012). Therefore, in recent years, various LMA optical fibers with special structure have been proposed. For example, Wang proposed a helical-core fiber (Wang et al. 2006), the core diameter is 30 μm, NA = 0.087, and the helix pitch is about 8.5 mm, which can support single mode operation. In 2014, Ma proposed a chirally coupled core (CCC) fiber with an octagonal central-core and 8 helical side cores (Ma et al. 2014), NA of the central-core is 0.068, and NA of side cores is 0.088. The helix pitch is 5.3 mm, the loss of LP_{01} mode is 0.2 dB/m near 1.0 μm, and they verified single-mode operation when fiber core exceeds 50 μm. The segmented cladding fiber (SCF) is another type of LMA fiber (Yang et al. 2022), which can support single mode operation when mode area is about 900 μm^2. In Ref. (Zhou et al. 2015), a supermode calculation method for tapered multicore fiber is proposed, and which is designed to enlarge mode area. Photonic crystal fiber (PCF) is a typical large mode field fiber model (Coscelli et al. 2014), which mainly focus on lowering NA of the core to reduce the number of modes and to enlarge single mode area. The largest core size of flexible PCF LMA fibers is approximately 40 μm, while the core size of rod-type PCF is close to 100 μm and is mainly used in laboratory. Ref. (Yehouessi et al. 2016) reported a large mode area pixelated Bragg fiber in which some high refractive index rods were placed in cladding, the core diameter is 35 μm and the effective mode area is 510 μm^2. Photonic bandgap fiber (PBGF) is another type of LMA PCF proposed by Chen et al. (Chen et al. 2023), the core diameter is 46 μm in the corner-to-corner direction, and the transmission spectrum is from 970 to 1180 nm. Malleville et al. recently proposed a new large-pitch fiber (LPF) (Malleville et al. 2021), the fiber geometry, relying on the modal sieve concept applied to an aperiodic cladding lattice, exacerbates the delocalization of higher-order modes (HOMs) out of the active core, the core diameter is higher than 70 μm. Gain-guided and index-antiguided (GG-IAG) fiber (Shen et al. 2017) has the largest single-mode core diameter (400 μm), but the loss is high and the laser efficiency is very low. Denisov et al. designed Leaky channel fiber (LCF) (Denisov et al. 2023), the core diameter is 22.5 μm, and when bending radius is 0.1 m, the fundamental mode (FM) loss is less than 0.1 dB/m in the spectral range from 0.9 μm to1.5 μm. Deepak Jain proposed multi trench fiber (MTF) in 2013(Jain et al. 2013), the fiber core can reach 100 μm, but the range of fiber parameters is relatively strict.

As mentioned above, some fiber structure is complex or the parameter range is strict, they are difficult to prepare. Some fiber core diameters are not large enough or loss is high. They obtained some specific applications, especially in the fields of 1.0 μm band. Since the thulium doped fiber laser reached the kilowatt level in 2018 (Gaida et al. 2018), it has not achieved higher power, the main reason may be the severe quantum loss of thulium ions, which leads to severe thermal effects and prominent nonlinear effects. In order to increase the mode area of Tm^{3+}-doped fiber lasers to overcome the adverse nonlinear effects. Recently, we proposed a novel type of heterogeneous helical cladding fiber (Shen et al. 2021a), the single mode core diameter is 60 μm, but there is no isolation ring between the core and the cladding, the loss and beam quality issues caused by boundary scattering (Because the cladding is composed of two materials spliced together) is serious (Shen et al. 2021b). In order to improve the performance of this new type of LAM fiber, now, an inner isolation ring is added between the heterogeneous helical cladding and the core in this paper, named as HHCR fiber, mode transmission performance of straight and bent fiber are both analyzed. Simulation results show that the fiber can be in an efficient single-mode working state when fiber core diameter is up to 60 μm. Isolation ring improves fiber core interface, which will furtherly ensure good beam quality based on single-mode operation. Simultaneously, the fiber structure is all-solid state that facilitates cutting, splicing, and other operations.

The HHCR fiber structure is showed in Fig. 1a is the cross section of the HHCR fiber, and (b) is the three-dimensional (3D) perspective graphics of the HHCR fiber. There is an added inner isolation ring between the core and the heterogeneous helical claddings, which will prevent the light in the core from leaking into the higher index cladding to improve the output spot quality. The radius and refractive index (RI) of the core are r and n_0, respectively. The thickness and RI of the isolation ring is d and n_1, respectively. The inner cladding consists of two different materials (RI of which are n_2 and n_3 respectively), and the radius is R_1. The outermost layer is the outer cladding, and the corresponding radius and RI are R_2 and n_3.The helix pitch of the fiber is Λ. The center angle of the n_2 cladding is θ. The relationship among n_0, n_1, n_2 and n_3 is $n_0=n_2>n_1=n_3$, when light transmitted in the core, it will be coupled into n_2 cladding, however, more HOMs power is coupled into n_2 cladding, less FM mode power is coupled. Therefore, through parameter optimization design, HOMs can be filtered out while retaining FM for transmission in the fiber core.

2 Coordinate transformation technique

In order to simulate the mode transmission performance of the HHCR fiber, a coordinate transformation method was adopted (Wong et al. 2012; Nicolet et al. 2008), thus, we can use a 2D simulation model to simulate the 3D HHC fiber. Firstly, a helicoidal coordinate system (ξ_1, ξ_2, ξ_3) can be deduced from the Cartesian coordinate system (x, y, z) in the following way (Nicolet et al. 2004):

$$\begin{cases} x = \xi_1\cos(\beta\xi_3)+\xi_2\sin(\beta\xi_3) \\ y = -\xi_1\sin(\beta\xi_3)+\xi_2\cos(\beta\xi_3) \\ z = \xi_3 \end{cases} \tag{1}$$

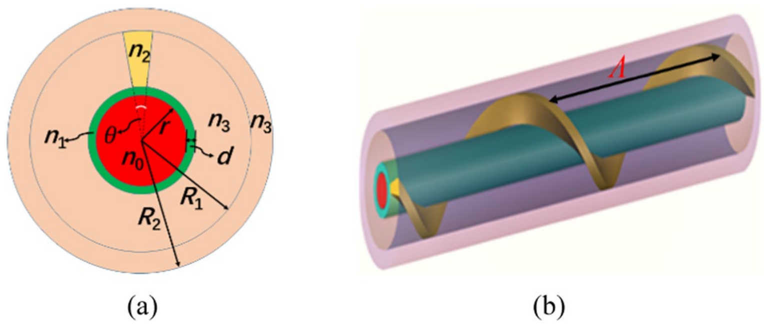

Fig. 1 **a** Cross section of the HHCR fiber, **b** 3D perspective graphics of the HHCR fiber

β is the angular twist rate, $\beta = 2\pi/\Lambda$. $\beta > 0$ corresponds to a left-handed helical twist. Equation (1) describes a mapping between the helicoidal coordinate system and the Cartesian coordinate system. The relationship between them can be expressed by Jacobian matrix as:

$$J_{\mathrm{h}}(\xi_1,\xi_2,\xi_3) = \frac{\partial(x,y,z)}{\partial(\xi_1,\xi_2,\xi_3)} = \begin{bmatrix} \cos(\beta\xi_3) & \sin(\beta\xi_3) & \beta\xi_2\cos(\beta\xi_3) - \beta\xi_1\sin(\beta\xi_3) \\ -\sin(\beta\xi_3) & \cos(\beta\xi_3) & -\beta\xi_1\cos(\beta\xi_3) - \beta\xi_2\sin(\beta\xi_3) \\ 0 & 0 & 1 \end{bmatrix} \tag{2}$$

Although the helicoidal coordinate system is not orthogonal, the Maxwell equations will still maintain the same form. What needs to be changed is to replace the original material permittivity ε and permeability μ with equivalent inhomogeneous anisotropic ones. The equivalent replacement formula is $\varepsilon_{\mathrm{h}} = \varepsilon \mathrm{T_h}^{-1}$, $\mu_{\mathrm{h}} = \mu \mathrm{T_h}^{-1}$(Napiorkowski and Urbanczyk 2014). T is the transformation matrix.

$$T_h(\xi_1,\xi_2) = \frac{J_h^T J_h}{\det(J_h)} = \begin{bmatrix} 1 & 0 & \beta\xi_2 \\ 0 & 1 & -\beta\xi_1 \\ \beta\xi_2 & -\beta\xi_1 & 1 + \beta^2(\xi_1^2 + \xi_2^2) \end{bmatrix} \tag{3}$$

The inverse matrix is:

$$T_h^{-1}(\xi_1,\xi_2) = \begin{bmatrix} 1 + \beta^2\xi_2^2 & -\beta^2\xi_1\xi_2 & -\beta\xi_2 \\ -\beta^2\xi_1\xi_2 & 1 + \beta^2\xi_1^2 & \beta\xi_1 \\ -\beta\xi_2 & \beta\xi_1 & 1 \end{bmatrix} \tag{4}$$

Thus, a helical fiber can be studied on the basis of a 2D simulation model. Compared with a 3D simulation model, this method retains the complete information of electromagnetic phenomena, reduces calculation time and computer resources.

3 Calculation theory of the HHCR *fiber* performance

Finite element modeling (FEM) is usually used to analyze the mode characteristics of optical fibers with complex structures (Napiorkowski and Urbanczyk 2014). Here, Comsol software is selected to simulate the HHCR fiber. Mode transmission loss, mode field area and bending characteristics are all analyzed based on the following theories (Saitoh and Koshiba 2003; Tsuchida et al. 2005).

3.1 Mode transmission loss

Transmission loss is an important performance of an optical fiber. The loss coefficients of LP_{01}, LP_{11} and LP_{21} modes are expressed as L_{01}, L_{11} and L_{21} respectively. The calculation formula is as follows:

$$L = \frac{40\pi}{\ln(10)\lambda}\mathrm{Im}\left(n_{\mathrm{eff}}\right) \tag{5}$$

n_{eff} is the effective RI of modes, $\mathrm{Im}(n_{\mathrm{eff}})$ is the imaginary part of neff, and λ is the light wavelength.

3.2 Effective mode area

Effective mode area (A_{eff}) is an important parameter to measure the power density of optical fiber. A_{eff} can be expressed as:

$$A_{eff} = \frac{(\iint \left|E(x,y)^2\right| dxdy)^2}{\iint |E(x,y)|^4 dxdy} \tag{6}$$

E (x, y) is the transverse electric field component of the fundamental mode. It can be seen from Eq. (6) that the wider the transverse electric field distribution of the fiber section, the larger the effective mode area of the fiber.

3.3 Bending loss

The fiber bending loss can be calculated according to Eq. (7).

$$n' = n(1 + \frac{x}{\rho R}) \tag{7}$$

where, n is the initial RI of the optical fiber, n' is the distribution of RI of a bending fiber, ρ is the photoelastic coefficient and the value is about 1.25 for silica fiber, R denotes bending radius, and x denotes the displacement from the center of the core in the curvature axis.

4 Numerical simulation results and discussions

The effects of the HHCR fiber parameters such as Λ, r, R_1, R_2, d, λ, n_0, n_1, n_2, n_3 and θ on the mode transmission characteristics are discussed next based on a Tm^{3+}–doped fiber. The isolation ring and claddings can be made from pure silica glass and the RI of which is 1.438 at the wavelength of 2.0 µm. So we set $n_1 = n_3 = 1.438$.

4.1 Mode transmission loss

4.1.1 The effects of RI

RI has important influence on transmission loss coefficients. Figure 2a illustrates the variation of L_{01}, $L_{11}$and L_{21} with n_0 (n_2). L_{01}, L_{11} and L_{21} all decrease with the increase of n_0 (n_2). When n_0 (n_2) = 1.439, d = 4 µm, L_{01} = 0.04 dB/m, L_{11} = 9.8 dB/m, L_{21} = 24.7 dB/m. When d = 2 µm, L_{01} = 0.05 dB/m, L_{11} = 12.4 dB/m, L_{21} = 37.9 dB/m. The thicker d, the smaller the loss, when d = 0, L_{01} = 0.24 dB/m, L_{11} = 18.65 dB/m, L_{21} = 27.86 dB/m, the loss of foundation mode (FM) is the largest. The simulation results show that the HHCR fiber can suppress high order modes (HOMs) efficiently. Figure 2b plots the variation of L_{01}, L_{11} and L_{21} with n_1 (n_3). It can be seen from the figure that the change of n_1 (n_3) has little effect on the loss. Therefore, the RI of the related claddings has a wide selection range, and it is helpful for optical fiber fabrication.

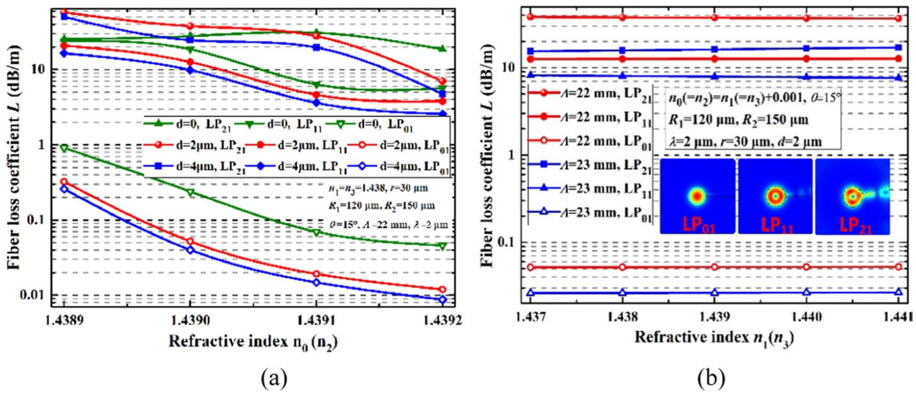

Fig. 2 **a** The effects of n_0 (n_2) on loss, **b** The effects of n_1 (n_3) on loss

4.1.2 The effects of *r*

The relationship between loss coefficient L, effective mode area A_{eff} and core radius r is showed in Fig. 3. With the increase of r, L_{01} is all lower than 0.1 dB/m when $\theta = 13° \sim 15°$, L_{11} basically has a downward trend. When $r = 30$ μm, $L_{01} = 0.05$ dB/m, $L_{11} = 12.6$ dB/m, and the corresponding effective mode area reaches 2010 μm^2. The mode discrimination has reached the international level (Jain and Sahu 2016). Simultaneously, when $\theta = 14° \sim 15°$, $r = 32$ μm, $L_{11} \geq 3.97$ dB/m, it also can suppress HOMs with a longer fiber.

4.1.3 The effects of *λ*

Figure 4 plots the variation of loss coefficients with wavelength λ. When λ changes from 1.98 μm to 2.02 μm, L_{01} is about 0.05 dB/m, which is very beneficial to laser amplification. L_{11} and L_{21} also keep higher than 10.0 dB/m. This means that the fiber can maintain SM operation at 2.0 μm.

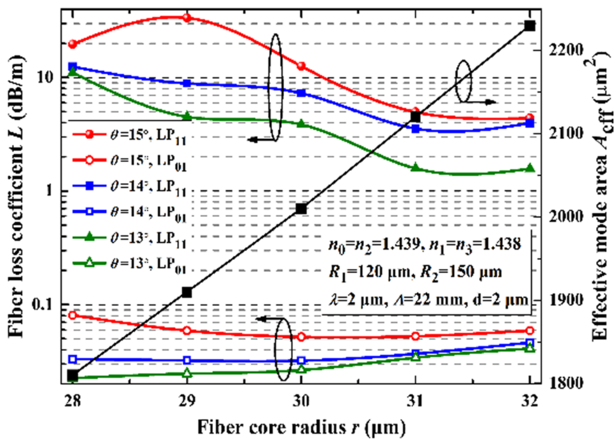

Fig. 3 The effects of r on loss coefficients and A_{eff}

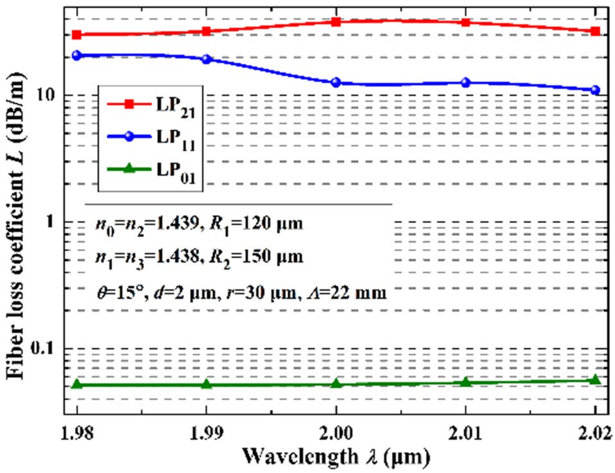

Fig. 4 The effects of wavelength λ on loss coefficients

4.1.4 The effects of Λ

The relationship between helix pitch Λ and loss coefficients is showed in Fig. 5. The transmission loss decreases with the increase of Λ. Meanwhile, the larger the thickness d, the lower the loss. When Λ is 22 mm ~ 23 mm and $d = 2$ μm-4 μm, $L_{01} < 0.1$ dB/m and $L_{11} \geq 6.3$ dB/m. This means the fiber has a good mode discrimination and a wide adapted range for Λ and d to fabricate the fiber. When Λ is 21 mm, $L_{01} > 0.2$ dB/m, it is not beneficial to laser amplification, so it is not suitable for fiber lasers.

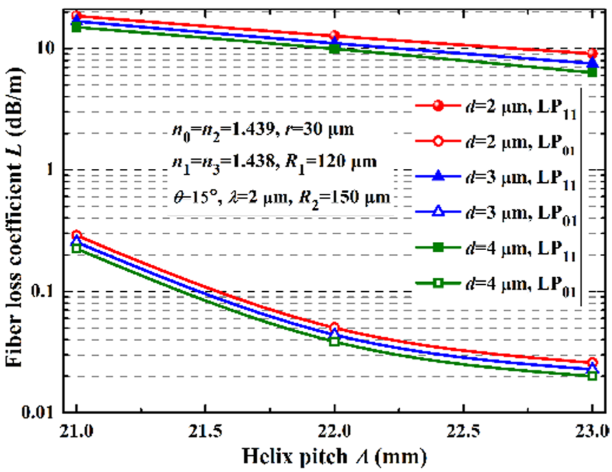

Fig. 5 The effects of helix pitch Λ on loss coefficients with different d

4.1.5 The effects of θ

The relationship between loss coefficients L_{01}, L_{11}, L_{21} and θ is showed in Fig. 6. When θ varies from 13° to 16°, L_{01}, L_{11} and L_{21} all increase. When $\theta = 13° \sim 15°$, $L_{01} < 0.052$ dB/m, $L_{11} > 3.6$ dB/m, $L_{21} > 16.6$ dB/m, the fiber can work as a LMA and SM fiber, especially, $\theta = 15°$ is an optimum parameter as a LMA and SM fiber. When $\theta = 16°$, 0.1 dB/m $< L_{01} <$ 0.2 dB/m, it is not the best choice for fiber lasers.

4.2 Bending characteristics

Considering the actual applications, it is necessary to study the bending characteristics of the HHCR fiber.

4.2.1 The effects of θ

In a bent optical fiber, a part of light cannot satisfy the condition of total internal reflection, so some light will escape from the fiber core, which will cause additional optical power loss. The effects of θ on bending loss are showed in Fig. 7. The loss can be effectively reduced by reducing θ value. When $\theta = 8°$, L_{11} is too small to suppress HOMs, when $\theta = 11°$, $L_{01} = 0.33$ dB/m, the loss of FM is high, and $\theta = 9° \sim 10°$ may be suitable for 0.4 m bending radius. In this case, Λ is 24 mm and is longer than that of the straight fiber discussed above.

4.2.2 The effects of r

Figure 8 depicts the bending loss changes with the fiber core radius r. When $r \in (28, 32)$ μm, $L_{01} < 0.18$ dB/m, $L_{11} > 7.29$ dB/m, the fiber is suitable for single mode operation. The single mode core diameter is up to 64 μm. When the core radius increases, the outer diameter of the cladding does not change, resulting in a thinner cladding. However, when the fiber is bent, the radiation effect is enhanced, resulting in increased losses of FM.

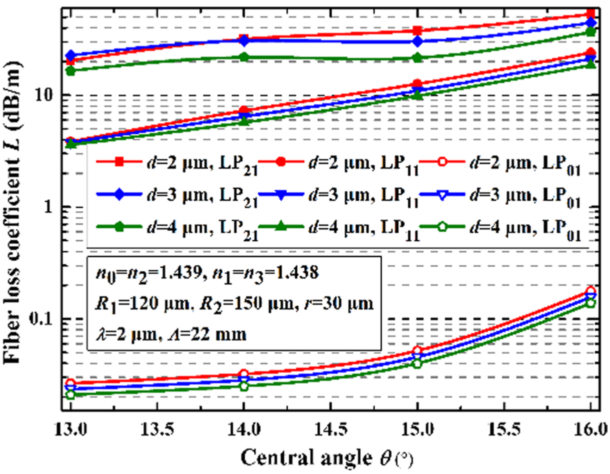

Fig. 6 The changing trend of L_{01}, L_{11} and L_{21} with θ

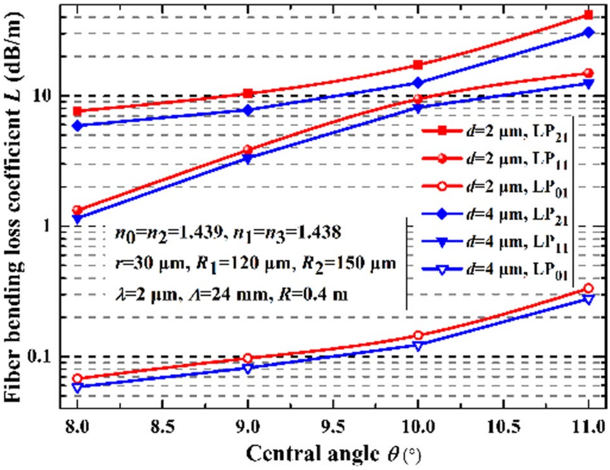

Fig. 7 The effects of θ on loss coefficients when the fiber is bent

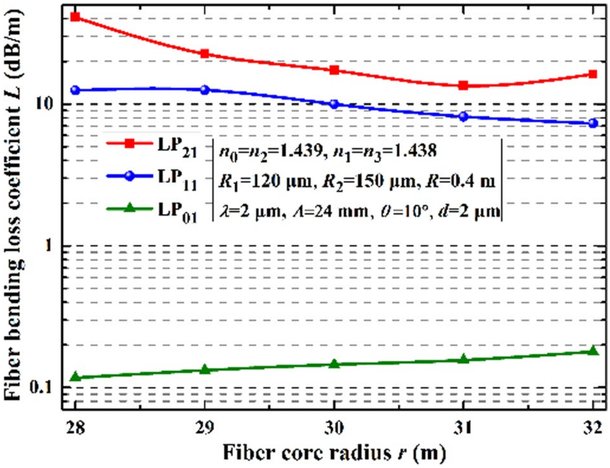

Fig. 8 The effects of r on bending loss for the bending fiber

4.2.3 Bending radius *R*

It can be seen from Fig. 9 that with the increase of bending radius R, the bending loss will decrease. The minimum bending radius R should be 0.4 m. When the bending radius R is 0.5 m, the bending loss of LP_{11} mode is 5.59 dB/m, if R increases furtherly, it may be difficult to filter out HOMs efficiently. Therefore, the suitable bending radius of the improved HHC fiber for single-mode operation is about 0.4 m ~ 0.5 m, and the corresponding mode field area range is 1938 μm^2 ~ 1950 μm^2.

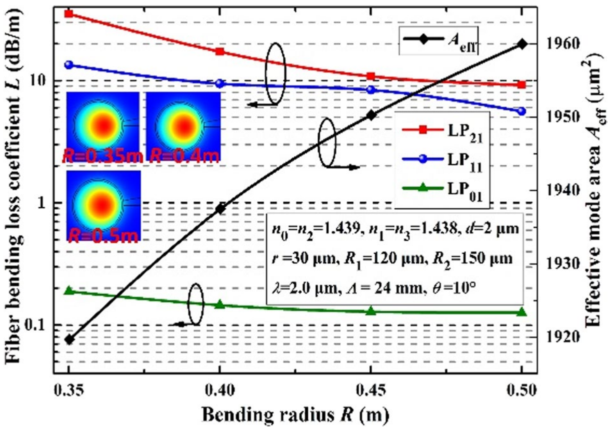

Fig. 9 Bending loss and mode area of the fiber for the bending fiber

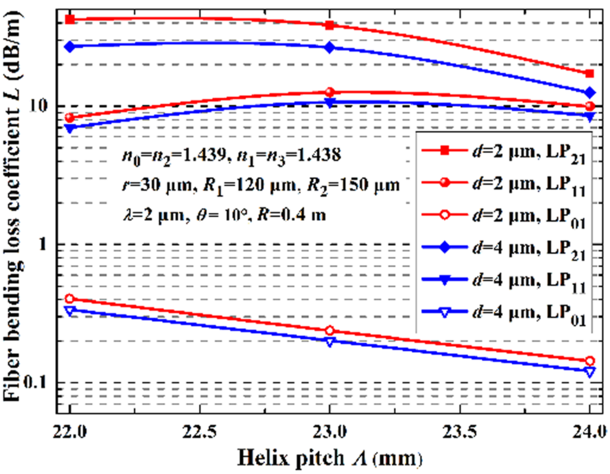

Fig. 10 The effects of helix pitch Λ with different d for the bending fiber

4.2.4 The effects of Λ

Helix pitch Λ also influence the bending loss, as showed in Fig. 10, L_{01} decreases with the increase of Λ, when $\Lambda = 24$ mm and $d = 4$ μm, $L_{01} = 0.12$ dB/m and $L_{11} = 8.5$ dB/m, HOMs can be suppressed efficiently, So the optimum value of Λ is 24 mm, which is longer than that of the straight fiber.

4.2.5 The effects of λ

As shown in Fig. 11, with different bending radius R, L_{21}, L_{11} and L_{01} all change slightly, this means that the mode discrimination is adapted to a wide wavelength range. When $R = 0.4$ m, $\lambda = 2.0$ μm, $L_{01} = 0.14$ dB/m, $L_{11} = 9.98$ dB/m, the HHCR fiber can efficiently suppress HOMs and keep single mode operation.

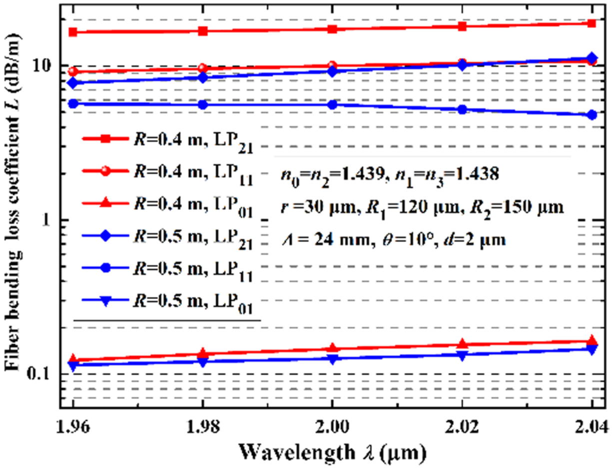

Fig. 11 The effects of λ on loss coefficients for the bending fiber

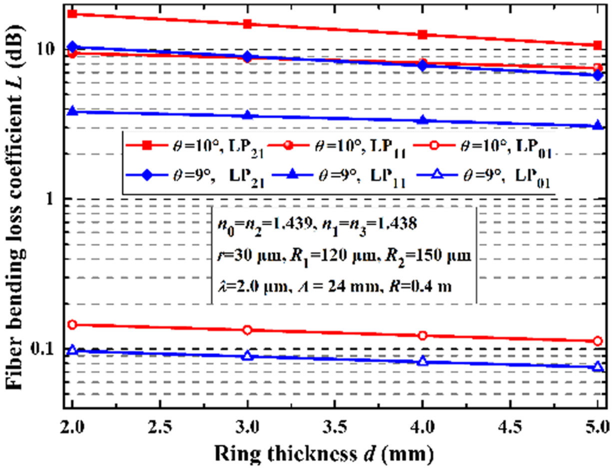

Fig. 12 The effects of d on loss coefficients for the bending fiber

4.2.6 The effects of *d*

The isolation ring plays a key role in the HHCR fiber. As showed in Fig. 12, L_{01}, L_{11} and L_{21} all decrease with the increase of *d*. Because a thicker ring will prevent the light in the core from radiating into the cladding. For $\theta = 10°$ and $d \in (2, 5)$ μm, L_{01} changes from 0.14 dB/m to 0.11 dB/m, L_{11} changes from 9.4 dB/m to 7.5 dB/m. This shows there is a wide range of *d* can be used to fabricate the fiber.

5 Conclusion

In this paper, we proposed a novel type of HHCR fiber, and mode transmission loss and bending characteristics are both analyzed based on the coordinate transformation technique and FEM. The effects of fiber parameters such as Λ, r, R_1, R_2, R, d, λ, n_0, n_1, n_2, n_3 and θ on the transmission loss of the HHCR fiber are analyzed in detail. For a straight fiber, the optimized parameters are $\Lambda = 22$ mm ~ 23 mm, $\theta = 13° \sim 15°$, $R_1 = 120$ μm, $R_2 = 150$ μm, n_0 (n_2) = 1.439 ~ 1.4392, n_1 (n_3) = 1.437 ~ 1.441, $d = 2$ μm ~ 4 μm, $\lambda = 1.98$ μm ~ 2.02 μm, the single mode core diameter is 60 μm and the effective mode area is 2010 μm^2. When the fiber core is heavily doped or used as the final amplification stage of a fiber amplifier, a shorter fiber is required sometimes, and the fiber can be used without bending. For a bent fiber, the optimized parameters are $\Lambda = 24$ mm, $\theta = 9° \sim 10°$, n_0 (n_2) = 1.439, n_1 (n_3) = 1.438, $R_1 = 120$ μm, $R_2 = 150$ μm, $d = 2$ μm ~ 5 μm, $R = 0.4$ m ~ 0.5 m, $\lambda = 1.96$ μm ~ 2.04 μm, the single mode core diameter is up to 64 μm and the maximum effective mode area is 1950 μm^2. For a traditional fiber, the single mode core diameter is only 28.5 μm according to the used refractive index ($n_{core} = 1.439$, $n_{cladding} = 1.438$) calculated by V-parameter theory, the single mode core area of the HHCR fiber is about 5 times that of the traditional fiber. Thus, the laser power that can be withstood by the HHCR fiber is 5 times that of it, and the non-linear threshold will also be significantly improved. The core diameter of Tm-doped single mode fiber from Nufern Company is about 20 μm, and compared to it, the core area of the HHCR fiber is 10.24 times that of it. The simulation results illustrate the HHCR fiber can suppress HOMs and keep single mode operation efficiently, and the isolation ring can improve the beam quality. The HHCR fiber can be obtained by rotating the preform when it is drawing, the helix pitch is more than 20 mm and is longer than other helical fibers as mentioned above, so it is relatively easier to drawing. What′s more, the fiber adopts an all solid state structure, which is conducive to cutting and splicing, etc. This new type of fiber may have important applications in high power fiber lasers.

Author contributions The authors completed the research and writing of this paper together. All authors reviewed the manuscript.

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Data availability Not applicable.

Declarations

Confict of interest The authors declare that they have no competing interests.

Ethical approval Not applicable.

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