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Loss characteristics of helical-core fiber*

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A special optical fiber is investigated, which has a helical core in the cylindrical cladding. The beam propagation method (BPM) is used for analyzing the impacts of the geometric and physical parameters on the properties of mode losses of the helical-core fiber. The propagation loss is 0.32 dB/m for the fundamental mode and the propagation loss is 20.95 dB/m for the LP_{11} mode in the wavelength range of 1050−1065 nm when the core diameter is 19 μm, the pitch of the core's helix is 2.66 mm, and the offset of the helix core from the center of the fiber axis is 31 μm. The core diameter of the single-mode helical-core fiber well exceeds that of the conventional large-mode-area fiber. The helical-core fiber can provide the effective large-mode-area single-mode operation without coiling fiber or selecting excitation mode.

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The large-mode-area fibers are used for reducing optical damages and nonlinear effects. The mode area is increased by lowering the numerical aperture of core and increasing the diameter of core[1]. Nevertheless, if the fiber becomes multimoded for large core size, it will cause the unstability of output laser beam and reduce the beam quality. Therefore modal discrimination techniques are required to achieve single-mode operation. The single-mode operation in the large core fiber laser can be achieved by coiling fiber to suppress higher-order modes. But bending of the fiber deforms the mode field distribution and reduces the mode area, which limits the benefit of large core[2,3]. Recently, some researchers have shown intense interests on helical-core fibers, in which the core has a helical trajectory along the fiber axis[4]. The loss characteristics of fundamental and high-order modes in helical-core fiber were investigated according to the Marcuse's equivalent model[4]. By replacing the bending radius with the equivalent curvature radius of the helix, arbitrary bending radius could come true. The single-mode helical-core fiber has a large mode effective area and low nonlinear effect, and can be used in high power fiber lasers and amplifiers[5,6]. The propagation losses were 0.6 dB/m and 9 dB/m for the fundamental mode and LP_{11} mode, respectively, when helical-core fibers with pitches from 8.5 mm to 8.8 mm effectively transfer the fundamental mode and suppress the high-order modes[5,6]. However, the Marcuse's model is mainly applied for bending loss of the fundamental mode, and K. S. Kaufman's model can be used in the computation of the loss of high-order modes[7]. Z. Jiang[8] derived an improved semianalytic bend-loss model, but the mode loss of the helical-core fiber was based on the fundamental mode loss of 1 dB/m, which can lead to the inaccurate calculation results. Liu[9] designed the similar helical-core optical fiber, which has a large straight central core wrapped by a helical core. The high-order modes in the straight central core were coupled into the helical core, then the high-order modes can be bent loss, as a result, the single-mode fiber with large mode area can be obtained. The single-mode power scaling was demonstrated robustly in fiber laser systems[10,11].

The exact analysis of characteristics of helical-core optical fiber is still rare. The beam propagation method (BPM) is used for analyzing the impacts of the geometric and physical parameters on mode losses of the helical-core fiber in this paper. By optimization, large mode area fibers can be obtained, which have a low propagation loss for the fundamental mode and a relatively high propagation loss for LP_{11} mode.

The helical-core fiber is shown schematically in Fig.1. P is the pitch, defined as the distance along the length of the fiber, in which one full cycle of the rotation is completed. Q is the offset from the center axis, D is the core diameter of the fiber, fiber diameter is 125 μm, n_{co} is the core refractive index, and n_{clad} is the cladding refractive index.

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The bend loss of the helical-core fiber is acquired by replacing the bend radius with the equivalent curvature radius of the helix. The equivalent curvature radius is calculated from[4]:

$$R_{\mathrm{eff}} \approx Q + \frac{(P/(2\pi))^2}{Q} \approx \frac{(P/(2\pi))^2}{Q} \quad . \tag{1}$$

Based on the above Eq.(1), we can get any curvature radius by selecting a reasonable offset and a pitch. The single-mode operation can be obtained finally.

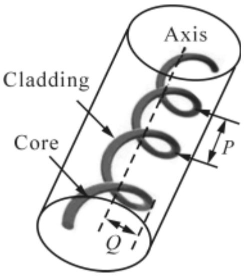


Fig.1 Schematic diagram of the helical-core fiber

The analytical solution is obtained difficultly due to the complex structure of the helical-core fiber. BPM has already been successfully applied to investigate various properties of optical fiber model[12]. Therefore, 3D-scalar BPM is used for analyzing the loss characteristics of the helical-core fiber. The relationship of the output power (square of the output amplitude) and the propagation distance L for LP_{01} and LP_{11} is shown in Fig.2, where D=14 μm, P=1880 μm, NA=0.1395, Q=30 μm, the refractive index difference between the core and the cladding is Δn=0.0067, and n_{clad}=1.4496 at λ=1064 nm. The output power values for LP_{01} mode and LP_{11} mode both have an exponential attenuation along the transmission distance, and small oscillations occur in the process of attenuation due to the fact that the launched mode is never only an eigen-mode at all points along a continuously varying curve. Hence, high-order modes are excited, and the coupling between these modes causes the power oscillations.

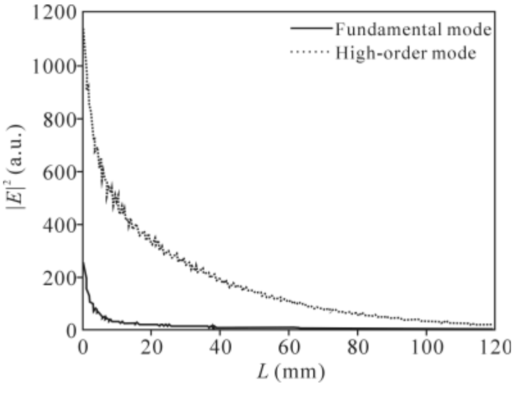


Fig.2 Output power for LP_{01} and LP_{11} modes

Now, we focus on the impacts of the pitch and the core diameter of the helical-core fiber on the mode loss. There are the same curvature radius and core diameter (R_{eff}=4 mm, D=14 μm) but different P and Q in Figs.3 and 4. However, the mode loss is obviously different. The larger Q is, the more mode loss can be caused for fibers with the same R_{eff}. Q can not be ignored to calculate the helical curvature radius when it is large. So Eq.(1) needs to be modified. Using the equivalent Marcuse's model for analyzing the properties of mode losses of the helical-core fiber consequentially suffers the error. In following calculation we will not use Eq.(1) any

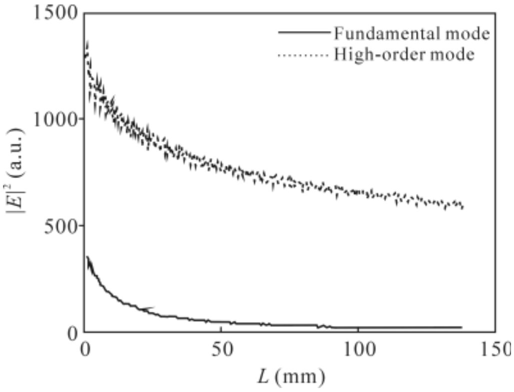
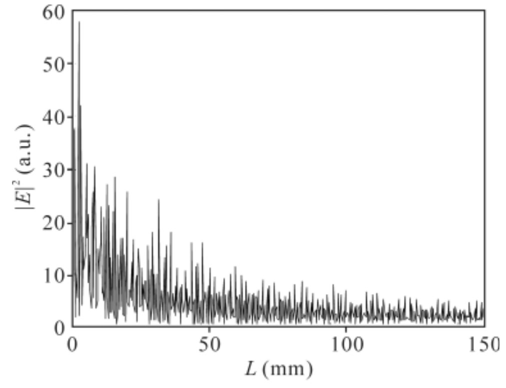
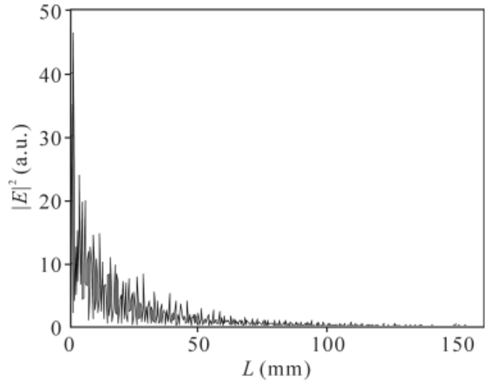


Fig.3 Output power for LP_{01} and LP_{11} modes versus propagation distance when Q=30 μm



(a) LP_{01}



(b) LP_{11}

Fig.4 Output power for LP_{01} and LP_{11} modes versus propagation distance when Q=40 μm longer.

Fig.5 illustrates the propagation losses α of LP_{01} and LP_{11} modes changing with the pitch. The parameters in Fig.5 are the same as those in Fig.2, except for D=15 μm. With increasing the pitch, both the fundamental mode loss and high-order modes loss decrease, which agree with the result of Marcuse's equivalent calculation. When the pitch is less than 2 mm, the losses of the fundamental mode and LP_{11} mode are particularly large, and small changes of the pitch can significantly affect the mode loss. This is also a challenge to the drawing of helical-core fiber. So we should choose larger pitch to reduce the fundamental mode loss, meanwhile to keep the loss of high-order modes small. Therefore, the pitch should not be too small, and we take the pitch range from 2.4 mm to 2.7 mm.

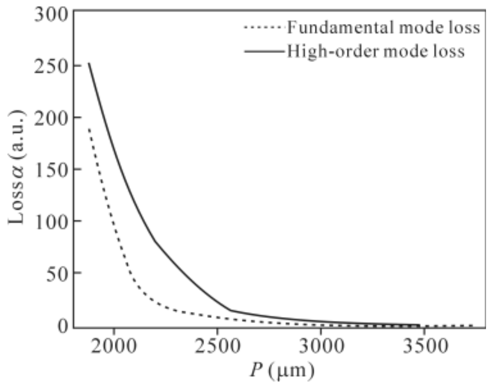


Fig.5 Propagation losses of LP_{01} and LP_{11} modes versus the pitch of helix

We define the mode loss difference between LP_{11} and LP_{01} modes as Δ, and $\Delta=\alpha_{LP_{01}}-\alpha_{LP_{11}}$. The mode loss differences for different pitches are shown in Fig.6. The maxima of the three curves always happen at D=19 μm. The LP_{11} mode loss is too small when the pitch is large. Finally, we select P=2.66 mm.

The effect of the core diameters on the propagation loss for a fiber with P=2.66 mm is illustrated in Fig.7. The curve oscillates and is non-monotonic. D has great influence on the fundamental mode loss. When D=14 μm and D=19 μm, the fundamental mode losses are minimal. In order to reduce the optical nonlinear effects, the optical fiber should be designed with large effective area as possible. In the step index profile, the mode effective area is increased by lowering the core refractive index and increasing the core diameter. According to Fig.6, we select D=19 μm and P=2.66 mm.

The relationships of the fundamental mode loss and Δ with the offset are shown in Fig.8. When Q is in range of 24−30 μm, the fundamental mode loss and Δ increase gradually with increasing Q. As Q=31 μm, both the fundamental mode loss and Δ reach extrema, which means that the fundamental mode has a minimum loss, and Δ has a maximum value. When Q only increases by 1 μm, the fundamental mode reaches a maximum loss, and Δ has a minimal value. When Q is in range of 32−36 μm, both the fundamental mode loss and Δ increase drastically. The precise selection of the pitch is needed to obtain a desired helical-core fiber. In accordance with the above analyses, we select Q=31 μm, where the loss for the LP_{01} mode is 1.95 dB/m, Δ is 16.44 dB/m, and the loss of LP_{11} mode is 10 times of that of LP_{01} mode.

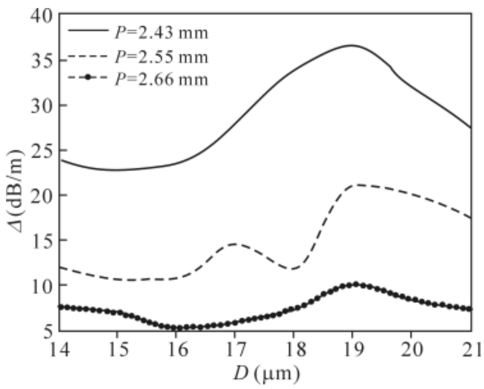


Fig.6 Mode loss difference versus the core diameter of helical-core fibers with different pitches

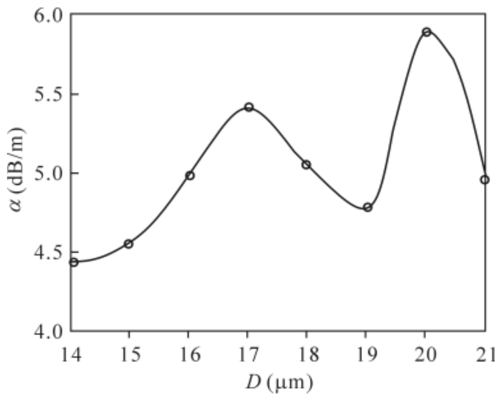


Fig.7 Fundamental mode loss versus the core diameter

We determine the optimal geometric parameters of helical-core fiber as P=2.66 mm, D=19 μm and Q=31 μm. The

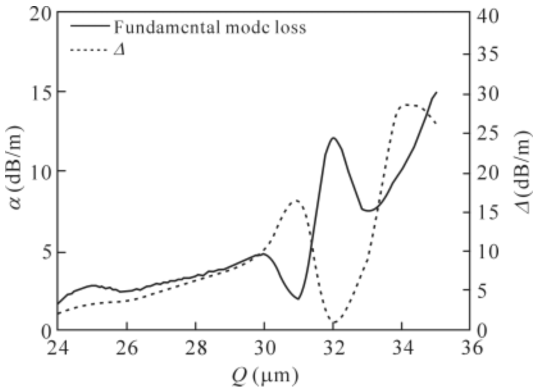


Fig.8 Fundamental mode loss and Δ versus the offset Q

effect of the refractive index difference ($\Delta n=n_{co}-n_{clad}$) on the fiber mode loss is also discussed. In a step index profile, the lower core refractive index is usually used for reducing the nonlinear effects. However, the difference between the core and cladding refractive indices can not be too large, so Δn is limited in the range from 0.0045 to 0.0070. Fig.9 shows the relationships of the fundamental mode loss and Δ versus Δn. When Δn increases, both the fundamental mode loss and Δ decrease gradually, and both have slight oscillations. When Δn=0.0066, LP_{01} mode loss is minimum as 0.39 dB/m, and the LP_{11} mode loss is 22.03 dB/m. The results indicate that helical-core fiber is good at wiping off higher-order modes to achieve the single-mode operation.

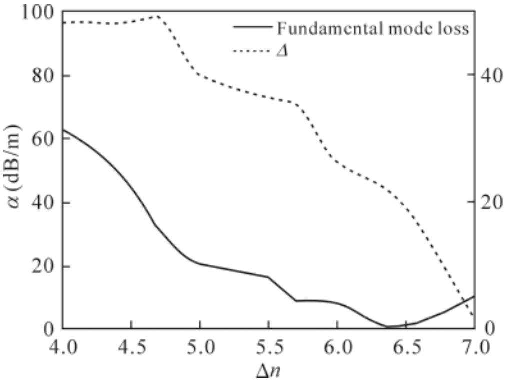


Fig.9 Fundamental mode loss and Δ versus the index difference

It is necessary to understand the spectral behavior of the helical-core fiber for the lasers application. The dispersion characteristics of optical fiber materials are fitted by Sellmeier equation[13]:

$$n_{\text{clad}}^2-1=\frac{0.6961663\lambda^2}{\lambda^2-(0.0684043)^2}+\frac{0.4079426\lambda^2}{\lambda^2-(0.1162414)^2}+\frac{0.8974794\lambda^2}{\lambda^2-(9.89616)^2}\ . \tag{2}$$

Fig.10 shows the dependence of the loss on the wavelength. The LP_{01} mode loss is 0.32 dB/m and the LP_{11} mode loss is 20.95 dB/m at 1.05 μm. It is noted that the higher-order mode can be eliminated, but the fundamental mode is maintained. The designed helical-core optical fiber has a lower fundamental mode loss but a larger high-order mode loss compared with Ref.[4].

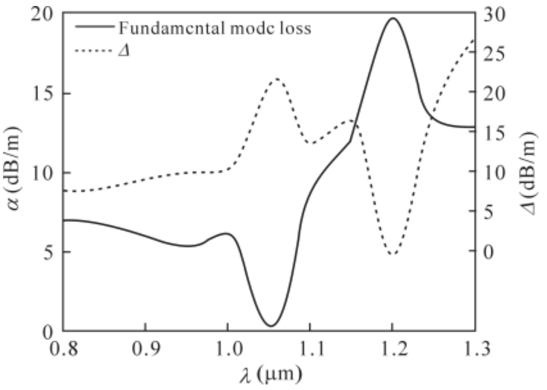


Fig.10 Fundamental mode loss and Δ versus the wavelength

In this paper, we use BMP to research the impacts of the geometric and physical parameters on the mode losses of the helical-core fiber. The way of eliminating high-order modes by optimizing geometric parameters of helical-core fiber is very effective. The propagation losses are 0.32 dB/m and 20.95 dB/m for the fundamental mode and LP_{11} mode, respectively. By the introduction of helical structure and the use of high power pump light source, the large-mode-area and single-mode operation fiber laser can be obtained. This paper can provide a reference for the study of high power laser and for the drawing of helical-core fiber in practice.

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