Optics Communications 410 (2018) 297–304

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Single-mode annular chirally-coupled core fibers for fiber lasers

Haitao Zhang *, He Hao, Linlu He, Mali Gong

Center for Photonics and Electronics, State Key Laboratory of Precision Measurement and Instruments, Department of Precision Instruments, Tsinghua University, Beijing 100084, China

A R T I C L E I N F O

Keywords:
Annular chirally-coupled core fiber
Fiber design
Fiber laser
Higher-order mode suppression

A B S T R A C T

Chirally-coupled core (CCC) fiber can transmit single fundamental mode and effectively suppresses higher-order mode (HOM) propagation, thus improve the beam quality. However, the manufacture of CCC fiber is complicated due to its small side core. To decrease the manufacture difficulty in China, a novel fiber structure is presented, defined as annular chirally-coupled core (ACCC) fiber, replacing the small side core by a larger side annulus. In this paper, we designed the fiber parameters of this new structure, and demonstrated that the new structure has a similar property of single mode with traditional CCC fiber. Helical coordinate system was introduced into the finite element method (FEM) to analyze the mode field in the fiber, and the beam propagation method (BPM) was employed to analyze the influence of the fiber parameters on the mode loss. Based on the result above, the fiber structure was optimized for efficient single-mode transmission, in which the core diameter is 35 μm with beam quality M^2 value of 1.04 and an optical to optical conversion efficiency of 84%. In this fiber, fundamental mode propagates in an acceptable loss, while the HOMs decay rapidly.

1. Introduction

High-power fiber lasers with diffraction-limited output beams are widely applied in many areas such as industry, medicine, telecommunications, and military [1–3]. Scaling the fibers to larger effective mode-field-diameter (MFD) ones helps decrease optical density, suppress the nonlinear effects such as stimulated Raman scattering (SRS) and stimulated Brillouin scattering (SBS), and as a result, increase the pulse energy and peak power of fiber lasers. For step-index fibers, prominent techniques for effective single-mode operations include matched excitation by particularly ion-doping [4], and higher-order mode (HOM) discrimination by bending [5]. However, these methods usually limit the core size less than 30 μm for diffraction-limited beam quality output. For instance, the beam quality factor M^2-value of the normal step-index fibers with core size of 35 μm will increase to 2.5 since too densely packed mode to discriminate the fundamental mode and its nearest neighbors. Utilizing microstructures, such as photonic crystal fibers (PCFs) [6] and large pitch fibers (LPFs) [7], very large mode area (VLMA, core diameter beyond 50 μm) fibers are developed for high energy lasers. However, microstructure VLMA fibers suffer monolithically integration difficulty (e.g. micro-structured fiber rods), as well as thermal-induced mode instabilities because the mode constraint ability of discontinuous boundary conditions of the core is much weaker than the continuous boundary ones [8]. The chirally-coupled core (CCC) fiber with a continuous core boundary combines robust single-mode laser performance in large cores (up to 55 μm demonstrated) [9] and stable mode even for high power laser output, while retaining the handling and packaging benefits associated with single mode fibers. The CCC fiber seems to be one of the most promising approaches for large mode and stable high power laser applications. However, except for the usage rights protections by CCC fiber patents (US7424193), the CCC fibers need eccentric preform for its helix side core. Meanwhile, many Chinese fiber manufacturers have the fiber processing technique with concentric preform, and they prefer the fiber structure based on the concentric preform to avoid the change of the fiber processing. Thus, a novel structure is designed and defined as annular chirally-coupled core (ACCC) fiber. The ACCC structure has an 82 μm-diameter multimode side annulus instead of the 16-μm side core in the common CCC fiber so that ACCC fiber can be drawn from a concentric side core preform instead of eccentric one of CCC.

The design principle of CCC fiber is to make the HOMs and the fundamental mode (FM) meet and do not meet the quasi-phase-matching (QPM) condition, respectively. This principle greatly improves the discrimination of the HOMs and FM losses [10]. Meanwhile, this principle also requires a small side core with very few modes. The smaller side core could decrease the number of the side modes and avoid

* Corresponding author.
E-mail address: zhanghaitao@mail.tsinghua.edu.cn (H. Zhang).

https://doi.org/10.1016/j.optcom.2017.10.003
Received 1 April 2017; Received in revised form 29 September 2017; Accepted 2 October 2017
0030-4018/

the FM matching the side modes. On the other side, a smaller margin between the losses of each mode is also sufficient to obtain the single mode preservation. For instance, in the design of the leakage channel fibers, the principles are 1 dB/m loss of HOMs and 0.1 dB/m for the FM [11], which are sufficient to suppress the propagation of HOMs and ensure negligible fundamental mode transmission loss. Furthermore, due to the mode competition, the margin between the losses of each mode could be even smaller. For the ACCC fiber, the side annulus can support many modes, and each mode of the side annulus can couple with modes in the center. Instead of calculating the QPM condition of all the modes, we present a novel design concept and procedure especially for the gain fiber operating in the fiber laser cavity. First, we used the beam propagation method (BPM) to calculate the difference of each mode's loss directly. Then, we optimized the ACCC structure parameter values by investigating the laser dynamic mechanism in active ACCC fibers. Using the output beam brightness as a judgment criterion, we could describe the performance of the ACCC fiber laser and ultimately optimized the structure definitely, considering both efficiency and beam quality.

In this paper, we firstly presented ACCC structure and explained why this novel structure is more suitable for Chinese manufacturing techniques. We used the finite element method (FEM) to simulate the mode field distributions in ACCC fibers and the BPM to calculate the losses. Based on the simulation results of the fiber mode discrimination for fiber passive propagation process, the rough range of ACCC structure parameter could be preliminarily determined. Then, we calculated the mode competition of the ACCC fiber lasers by exploring the laser rate equations and ultimately optimized the structure based on the brightness criterion. And it was demonstrated this new ACCC structure has the similar single-mode characteristics to common CCC fiber.

2. Annular chirally-coupled core fibers

As described below, there are still technical difficulties for manufacturing CCC fibers in China. The doped fiber core, i.e. high refractive index zone herein, is made by the modified chemical vapor deposition (MCVD) method, which involves the deposition inside a substrate tube for the fiber preform. First, limited by the MCVD technology, the diameter of the deposition zone in the preform is difficult to be larger than 5 mm. Second, the preform is usually very long so that the diameter of the preform should not be thinner than 6 mm, or it would be too fragile for further processing. These two restrictions determine the maximum doped zone and the minimum outside diameter dimension of the preforms. To fabricate the CCC fiber, we need to prepare two fiber preforms, a main preform for signal propagation and a side core preform for HOMs loss dissipation. The main preform needs to be drilled a proper hole to insert the side core preform. If we dope the center signal core to a maximum diameter of 5 mm by MCVD, we can design the whole preform structure as shown in Fig. 1(a), by scaling up the corresponding fiber dimensions in brackets. In the fiber, the 33-μm center core has a numerical aperture (NA) of 0.06, and the side core has a diameter of 16 μm and NA of 0.1. The distance between the two cores, measured from the edge of the center core to the middle of the side core, is 12 μm and scaled up to 1.8 mm for preform structure. If we used the concentric side core preform like Fig. 1(b), the diameter of the side core preform would be less than 3.6 mm, less than 6-mm preform limit and too thin for a long rod. One of the solutions is grinding the side core preform eccentrically, and making the doped core area close to the boundary, as in Fig. 1(c), which can enlarge the possible side core preform greater than 6 mm. This method, called fire-polishing, is applied by the fiber fabrication industry, however still needs time for Chinese manufacturers to realize. If we could magnify the size of the side core and keep the property of the fiber at the same time, we could use the current fiber producing process and reduce the cost.

To satisfy the manufacturing requirements in China, a novel fiber structure denoted as ACCC fiber is designed, as shown in Fig. 2. The

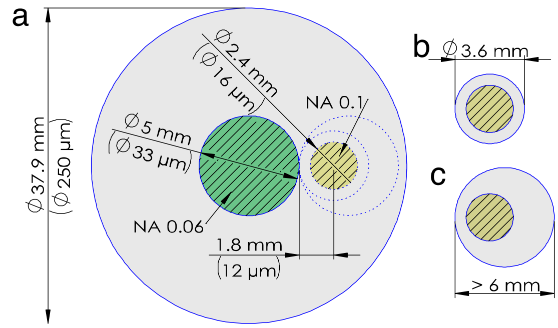

Fig. 1. (a) Structure of the main preform for CCC fiber. Numbers in brackets are the actual size of the fiber, and the dash line shows the drilling position for the side core preform. Hatchings show the doped cores in the fiber by MCVD. (b) Concentric side core preform. (c) Eccentric side core preform.

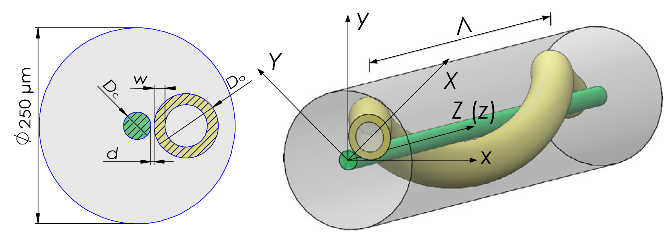

Fig. 2. ACCC fiber structure.

diameter of the center core D_c is 35 μm with NA of 0.06, similar with the common CCC fiber. On the other hand, the ACCC fiber structure has a larger helical side annulus, greatly reducing the difficulty of manufacturing the fiber preforms. In ACCC fiber, the outer diameter of the side annulus D_o could be up to 82 μm (NA0.1), therefore the diameter of side preform is about 12 mm, which is thick enough (much greater than 6 mm limitation) to satisfy the requirements of Chinese manufacturers. The helix pitch Λ of the side annulus, the width of the annulus w, and the inner distance between the two doped cores d affect the fiber characteristics and will be optimized in the following sections.

Because of the helix structure of CCC fiber, the cross section is associated with its z-coordinate value. Herein a helical coordinate system $\{X, Y, Z\}$ is introduced for the helix structure [12]

$$\begin{cases} X = x \cdot \cos \tau z + y \cdot \sin \tau z \\ Y = -x \cdot \sin \tau z + y \cdot \cos \tau z \\ Z = z \end{cases} \tag{1}$$

where $\tau = 2\pi/\Lambda$, $\{x, y, z\}$ is the Cartesian coordinate system, and zero point of the z axis is set at the position where x and X axes coincide. In the helical coordinate system, the shape of the fiber cross section decouples with Z direction, and the three-dimensional finite element problem degenerates into two-dimension, which decreases the calculation time. However, this coordinate system is not orthogonal, so the Helmholtz equation used in the FEM in the system needs to be further discussed. This equation is given by

$$\nabla \times (\nabla \times \boldsymbol{E}) - k_0^2 \varepsilon_h \boldsymbol{E} = 0 \tag{2}$$

where the k_0 is the wave number in a vacuum, and the ε_h is the relative permittivity tensor in the helical coordinates, which is constructed by applying Jacobian matrix $\boldsymbol{J}$ of the helical coordinate with respect to the Cartesian system

$$\begin{aligned} \varepsilon_h(X,Y,Z) &= \boldsymbol{J} \cdot \boldsymbol{\varepsilon}_c(x,y) \cdot \boldsymbol{J}^T \\ &= \begin{pmatrix} 1 & 0 & \tau Y \\ 0 & 1 & -\tau X \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \varepsilon_1(X,Y) & \varepsilon_6(X,Y) & \varepsilon_5(X,Y) \\ \varepsilon_6(X,Y) & \varepsilon_2(X,Y) & \varepsilon_4(X,Y) \\ \varepsilon_5(X,Y) & \varepsilon_4(X,Y) & \varepsilon_3(X,Y) \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ \tau Y & -\tau X & 1 \end{pmatrix}. \end{aligned} \tag{3}$$