Characteristics of pump mode distribution in a double-clad fiber with octagonal inner cladding

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We investigate the characteristics of pump mode distribution in a double-clad fiber with octagonal inner cladding by measuring the intensity profile of pump waves. The pump modes present an approximate flat-top distribution with a slight dip in the center of the inner cladding with normal fiber coiling. By twisting the normal fiber spool, the distribution of pump modes becomes more remarkably flat-topped for the improvement of pump absorption. The measured results could verify the validity of assuming the pump overlap integral factor as the area ratio of the doped core to the inner cladding. The deterioration of pump coupling efficiency causes the diffusion of pump modes, making against the pump absorption.

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1. Introduction

The rapid power scaling of high power fiber lasers in recent years mainly benefits from the cladding-pumped fiber technology [1]. In a double-clad fiber (DCF), however, pump waves propagate in the multimode inner cladding, leading to the poor pump absorption. Therefore, various methods have been proposed for the improvement of pump absorption, e.g., the double-pass pump schemes using a fiber Bragg grating and conical-shaped fiber end as a pump reflector [2-3] and a long-period fiber grating for coupling the pump radiation of the inner cladding into the doped core [4]. Nevertheless, the most direct and cost-effective approach is designing noncircular inner cladding geometries to overcome the circular symmetry [5], such as truncated circle-shaped, rectangular, D-shaped. Based on a three-dimensional beam propagation method, it has been shown that the pump absorption coefficient is constant along the fiber length in such noncircular DCFs, because the chaotic ray dynamics make the intensity distribution of all pump modes homogeneous [6]. For that reason, the overlap integral factor between the pump power distribution and ion-doped area, used for describing the effective pump absorption, can be approximately assumed as the area ratio of the doped core to the inner cladding in numerical simulations [7-8]. In addition, a hexagonal DCF with high absorption and low splice loss has been demonstrated recently [9]. Similarly, the octagonal DCF (ODCF) with more symmetric cross section has been widely used, especially in high power all-fiber lasers and amplifiers [10-11]. However, to the best of our knowledge, there has been little information available in literature about the pump absorption characteristic of the ODCF. As the pump absorption depends on the pump mode distribution, the pump absorption characteristics can be studied by analyzing the pump mode distribution. In this letter, we report on the investigation of pump mode distribution of the ODCF by measuring the intensity profile of pump waves under different launching conditions.

2. Experimental setup

The experimental setup for measuring the pump mode distribution is shown in Fig. 1. A laser diode with the central wavelength of 975nm and a maximum fiber-coupled output power of 50W, is used as the pump source. The pump power is launched into a 1.6m-long section of ODCF via collimating and focusing lens. For the high coupling efficiency, the latter lens is fixed on the fiber coupler with three-dimensional (3D) precise adjustment. The section of ODCF to be tested is a DCF without ion-doping, which has an octagonal-shaped inner cladding with the diameter of 400μm and numerical aperture (NA) of 0.46. The inset of Fig. 1 schematically shows the cross section of the ODCF. We use a laser beam profiler, namely BeamMaster (BM), to measure the intensity distribution of pump modes. By using seven knife-edges scanning technology, the BM could provide more accurate measurements of the cross-sectional and two-dimensional (2D) beam intensity profiles, which are displayed in real time on the screen of personal computer (PC). In view that the InGaAs sensor aperture of BM is only 5mm while the NA of ODCF is relatively large, the BM detector is laid nearly after the ODCF output port for the measurement of near-field spatial intensity profile.

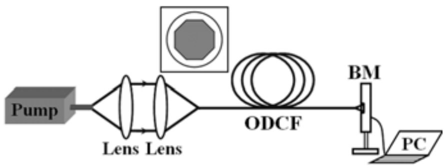

Fig. 1 Experimental setup. ODCF: Octagonal double-clad fiber. BM: BeamMaster. PC: Personal computer. The inset shows the cross section of ODCF.

3. Results and discussion

In general, an active DCF is spooled in fiber lasers and amplifiers. Thus, we first examine the characteristic of pump mode distribution in the ODCF coiled to the diameter of 18cm. The pump coupling system is adjusted precisely into the optimum state for the coupling efficiency of 70%, which means that the pump beam is focused on the center of the ODCF. Fig. 2(a) shows the measured 2D intensity profile of pump modes. Seen from this figure, most pump energy is centered in the inner cladding of the ODCF. For the detail of the mode distribution, the radial intensity variation along the V axis (See Fig. 2(a)) is shown in Fig. 2(b). Because of the circular symmetric distribution, the intensity variation along the W axis is similar to that shown in Fig. 2(b). It is clearly seen that the pump modes present an approximate flat-top distribution with a slight dip in the center of the inner cladding. In terms of the wave-guiding theory, the appearance of the slight dip indicates that there is a portion of the pump waves still existing in the form of high-order modes. The reason is that this kind of modes has more energy in the edge of the multimode cladding while has less in the center. According to the ray tracing approach, on the other hand, the octagonal-shaped structure has the circular symmetry to some extent, in which the caustic phenomenon resulting in spiral modes with annular distribution [12]. In essence, neither high-order modes nor spiral modes contribute to pump absorption.

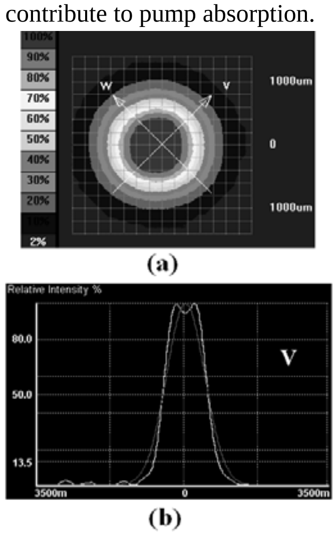

Fig. 2. Measured intensity distribution of pump modes with normal coiling. (a) 2D intensity profile; (b) radial intensity variation along the V axis. The reference line is Gaussian fit profile.

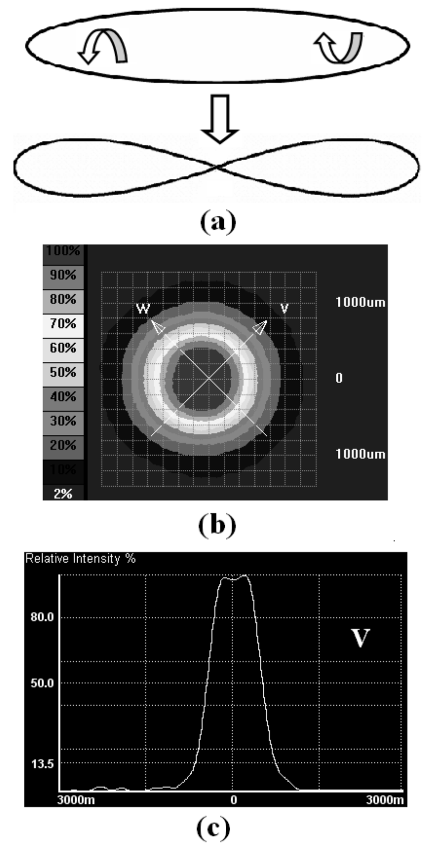

Fig. 3. (a) Schematic diagram of twisting the normal fiber spool. Measured intensity distribution of pump modes with mode scrambling: (b) 2D intensity profile; (c) radial intensity variation along the V axis.

Due to the mode coupling and transforming, the fraction of pump power carried by different pump modes varies along the fiber. Hence, for obtaining a stable spatial mode distribution, the pump waves are needed to propagate through a relatively long fiber. It is worth noting that the length of the tested ODCF in our experiment is only 1.6 meter, which may be short for stabilizing the mode distribution. However, the shortage can be compensated by mode scrambling. Taking that reason into account, we slightly twist the normal fiber spool as shown in Fig. 3 (a). In addition, similarly to bending fibers into kidney-shape or figure-eight-shape [9], the twisting also helps to mode mixing, so that the high-order modes or caustic modes could be coupled to absorbing modes [13].

Fig. 3 (b) and (c) show the measured intensity profile of pump modes two-dimensionally and radially, respectively. Compared to the normal coiling, the small dip in the center of the pump intensity profile has been slighter, as a result of the mode mixing. In other words, by twisting the normal fiber spool, the distribution of pump modes becomes more remarkably flat-topped than that without mode scrambling, which means the improvement of pump absorption. The relative regularity of the inner cladding structure in ODCF could be overcome thoroughly under an appropriate mode coupling condition, so that the pump power distributes uniformly in the inner cladding.

The measured result coincides with the numerical analysis that the pump intensity distribution can be approximated by a square profile [7]. Therefore, the validity of approximate assumption for pump overlap integral factor as described above in simulating a rare-earth-doped ODCF laser, is verified.

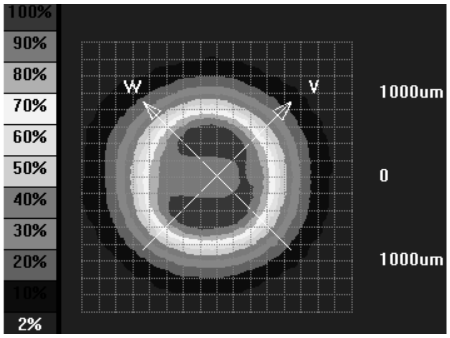

Fig. 4. Measured 2D intensity profile of pump modes with the deterioration of pump coupling efficiency.

The pump absorption efficiency also depends on the launching conditions [14], which is essentially due to the fact that the launching conditions have influences on the distribution of pump modes. To examine the influences, we make the pump coupling system out of the optimum state by adjusting the fiber coupler, with the coupling efficiency of 21% correspondingly. Fig. 4 shows the measured 2D intensity profile of pump modes in the ODCF. As shown in this figure, the pump energy would not concentrate in the center of the inner cladding any more, whereas diffusing into two petals. It indicates that with such launching condition most of the pump waves are excited in the form of high-order modes. On account of the pump diffusion, the interaction between ion-doped core area and pump power significantly declines, resulting in the decrease of pump absorption efficiency. The deterioration of pump coupling efficiency would limit not only the increase of launched pump power, but also the improvement of pump absorption efficiency. Thus, it is important to adjust the coupling system for the optimum launching efficiency.

4. Conclusions

We have measured the intensity distribution of pump waves in the ODCF for the investigation of pump mode characteristics using a laser beam profiler with multi-knife-edges scanning technology. The pump modes show an approximate flat-top distribution with a slight dip in the center of the inner cladding with a normal fiber spool. By twisting the fiber spool for mode scrambling, the distribution of pump modes becomes more remarkably flat-topped, hence more beneficial to the enhancement of pump absorption. It is verified that the validity of assuming the pump overlap integral factor as the area ratio of the doped core to the inner cladding. By varying the launching conditions, the pump energy diffuses with the deterioration of pump coupling efficiency.

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