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RESEARCH ARTICLE

Research on multi-kilowatts level tapered fiber bundle $N\times1$ pumping combiner for high power fiber laser

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Abstract Pumping combiner is a kernel component of high power fiber laser (HPFL). We demonstrate two types of tapered fiber bundle (TFB) end-pumping combiner able to combining multi-kilowatts of pumping laser. After the experimental test of coupling performance, the 3×1 coupler is proved to have a power handling capacity of 2.11 kW with a coupling efficiency of 95.1%, and the 7×1 coupler is capable of handling pumping power of 4.72 kW with a coupling efficiency of 99.4%. These two coupler have obtained the ability to be used in laser diodes (LDs) direct beam combining and the pumping coupling of multi-kilowatts level fiber lasers.

Keywords high power fiber laser (HPFL), pumping combiner, tapered fiber bundle (TFB)

1 Introduction

High power fiber laser (HPFL) has achieved extensively application in fields such as military, industry, medicine and research, and thus has become a worldwide research focus. Nowadays, the issues that used to be the Achilles' heel to HPFL, e.g., mode matching and thermal-induced effect, has been properly solved. Combined with the inherent high gain of fiber laser, the transition of pumping laser into output signal laser in HPFL now can be accomplished at a relatively high efficiency. Therefore, the approach to efficiently couple the high power pumping laser into the inner clad of the active fiber has been the hotspot in the research of HPFL. To achieve an kilowatt (kW) level HPFL, multi-kilowatts of pumping laser needs to be coupled into a inner clad whose diameter is typically at the level of several hundred micrometers. The difficulty of pumping coupling is self evident.

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Several techniques have been brought up aiming to solve that problem, including tapered fiber bundle (TFB) end coupling, GT-wave technique [1], the embedded lens side coupling [2], the embedded mirror side coupling [3], V-groove side coupling [4], the fiber angle polishing method [5], the diffraction grating side coupling [6], the all-fiber side coupling [7], etc. Among these techniques, the coupling plans that employ isolate optical components, due to issues like precise adjustment and instability, are not suitable to HPFL. On the other hand, the fine reliability, simple structure and high power capability have made the all-fiber pumping couplings the main pumping scheme in HPFL.

The all-fiber pumping combiners are usually divided into two genres based on different structures. One is $N\times1$ combiner, whose input fibers are made up by N pump fibers. The other is $(N+1)\times1$ combiner, whose input fibers contain N pump fibers and one signal fiber in the center of the bundle [8]. In this paper, we focus on the performance of $N\times1$ combiner.

Typically $N\times1$ end-pumping combiner is manufactured by bundling up pump fibers, melting and drawing the bundle into a taper and then fusion splicing it to the output fiber. Plenty of companies and research institutes have put numerous effort in researching and developing this coupling approach, including ITF, OFS, G&H, LightComm and so forth. In 2007, ITF laboratory reported a 7×1 TFB combiner carrying out a kW level laser beam combining [9]. Xiao et al. in 2011 demonstrated a 7×1 TFB combiner capable of 1 kW laser combining and 300 W laser splitting [10], and in 2013 demonstrated a 7×1 TFB combiner combining laser power of 3 kW [11]. Zhou et al. in 2015 reported a 3.8 kW laser beam combining via 7×1 TFB combiner [12].

In this paper, we reported the most recent progress in developing TFB end-pumping combiner. Through manufacturing process refinement and measuring system upgrade, a 3×1 TFB end-pumping combiner coupling laser of 2.1 kW and 7×1 TFB end-pumping combiner

coupling laser of 4.7 kW were achieved, which to the best of our knowledge represents the highest level of TFB combiner.

2 TFB combiner manufacturing

The manufacturing process of TFB end-pumping combiner is carried out through five steps: fiber preparation, fiber bundle melting and drawing, fiber end treatment, fusion splicing and packaging, the last four steps of which are illustrated in Fig. 1. After the fiber preparation, the fibers are gathered up in a bundle in a certain pattern. Then the bundle is heated until melted while drawn axially in the opposite directions into a dual-tapered section, as shown in Fig. 1(a). The dual-tapered section is then cut off where the diameter of the section equals that of the output fiber, as shown in Fig. 1(b). After treatment with the end, the fiber bundle is fusion spliced with the output fiber, as shown in Fig. 1(c). Finally, the combiner is packaged, as depicted in Fig. 1(d).

Based on the manufacturing process mentioned above, several types of TFB end-pumping combiner have been developed, such as 3×1, 7×1, 19×1, 37×1 and 61×1 combiner. Figure 2 are the cross section of the fiber bundles of the combiners. Among these combiners, there are two types that are specially designed for the employment in HPFL. One is 3×1 TFB end-pumping combiner, whose input fiber and output fiber have a core and clad diameter of 200/220 μm and 400/440 μm, and an identical core NA of 0.22. The other one is 7×1 TFB end-pumping combiner, whose input fiber and output fiber have a core and clad diameter of 200/220 μm and 400/550 μm, and a core NA of 0.22 and 0.46, respectively. Owing to the common usage in HPFL, considerable researches and experiments have been done on these two combiners. Via the refinement of the fixture of fiber bundle, the temperature control in the melting and drawing process and the optimization of drawing parameter, the performance of the combiners has been significantly improved.

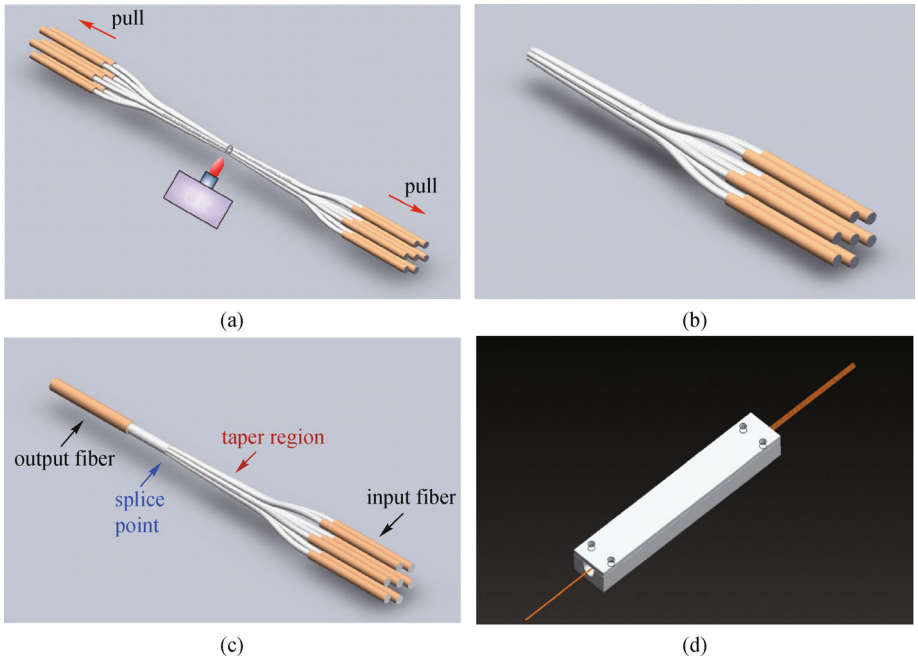

Fig. 1 Manufacturing process of TFB end-pumping combiner

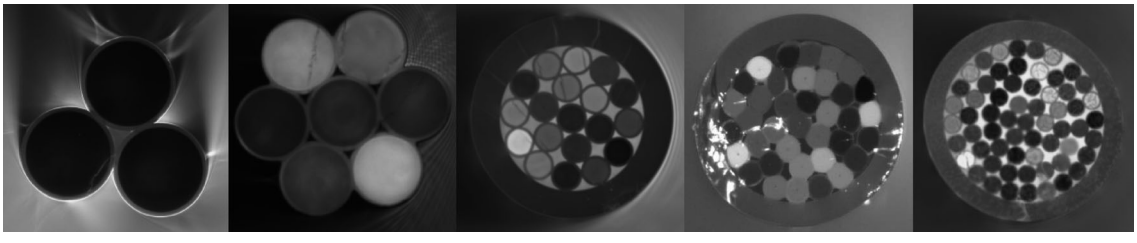

Fig. 2 Cross section of the fiber bundles of different combiners

3 Experimental results

3.1 3×1 TFB end-pumping combiners

Carrying out test of the performance of 3×1 TFB end-pumping combiners, we started with the coupling efficiency. As illustrated in Fig. 3, by fusion splicing a single input fiber with the pigtail of a pumping laser diode (LD), the laser power at the output fiber was measured. After cutting off the splice and measuring the input pumping power at the pigtail of the LD, the coupling efficiency of that single input fiber was calculated. To couple the pump laser with full NA, the parameters of pigtail of the pumping LD was selected to match those of the input fiber.

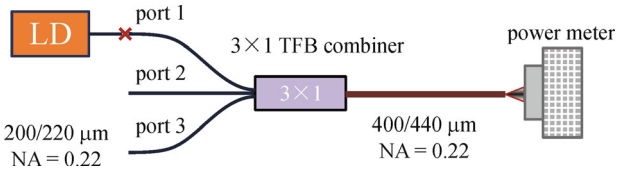

Fig. 3 Schematic of the experimental setup for the test of coupling efficiency

Switching the input fiber, the coupling efficiencies of all the input were acquired, which are 95.4%, 96.0% and 93.9%, averaged at 95.1%.

Next, we carried on with testing the power handling capacity with the experiment depicted in Fig. 4. The 3×1 combiner was pumped by three LDs, each with a pump power of 650 W, a core and inner clad diameter of 200/220 μm and a NA of 0.22. Finally, with the pumping power launched at 2218 W, an output power of 2110 W and total coupling efficiency of 95.1% was achieved.

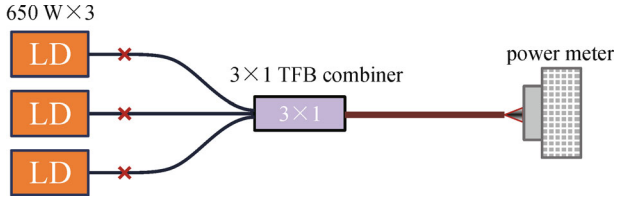

Fig. 4 Schematic of the test of power handling capacity of 3×1 combiner

The variation of output power of 3×1 combiner with the pumping power is shown in Fig. 5. There is evident no degeneration of coupling efficiency during the increase of the pumping power. Hence, it is safe to conclude that the power handling capacity is more than 2.11 kW.

3.2 7×1 TFB end-pumping combiners

The test of coupling efficiency of 7×1 TFB combiner followed the same procedure of 3×1 TFB combiner. Shown in Fig. 6, the coupling efficiency of single input averages out at 99.41%, with maximum value of 99.6% and minimum value of 99.1%.

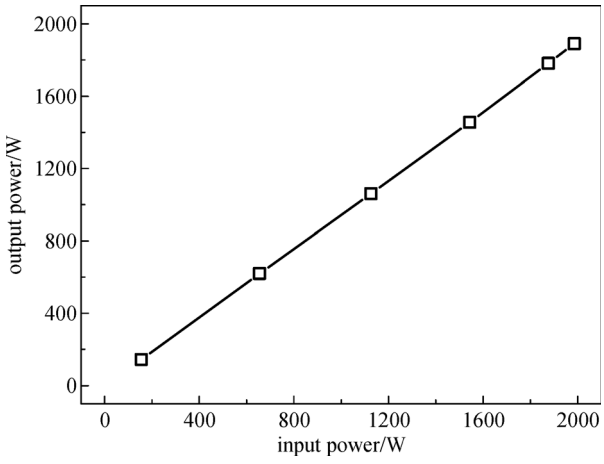

Fig. 5 Output power of 3 × 1 combiner versus pumping power

The test of power handling capacity of 7×1 combiner was performed as illustrated in Fig. 7. Pumped by seven LDs which share the same parameters with the LDs in the 3×1 test, the 7×1 TFB end-pumping combiner achieved

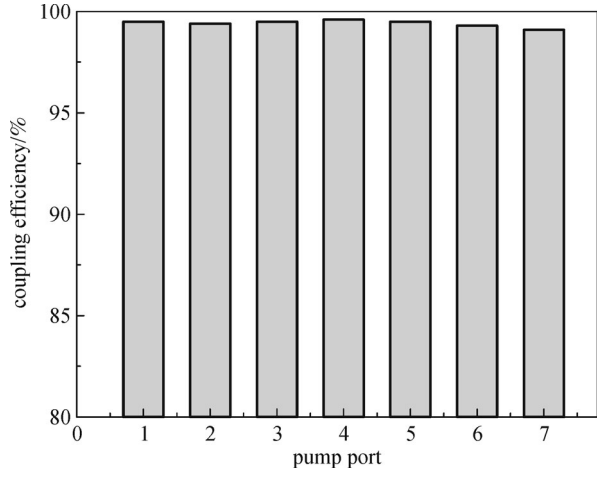

Fig. 6 Coupling efficiency of single input of 7×1 combiner

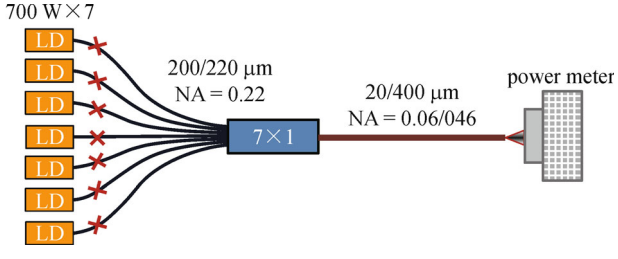

Fig. 7 Schematic of the test of power handling capacity of 7×1 combiner

an output power of 4720 W at the pump power of 4748 W with a total coupling efficiency of 99.4%, as shown in Fig. 8.

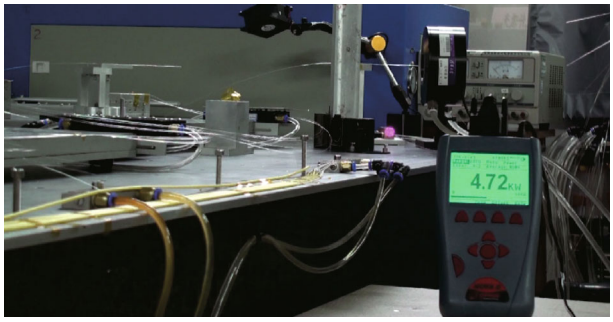

Fig. 8 Photo of the test of power handling capacity of 7×1 combiner

Figure 9 depicts the relationship between the output power of 7×1 combiner and the pumping power. The total coupling efficiency remains constant, verifying the power handling capacity of no less than 4.72 kW.

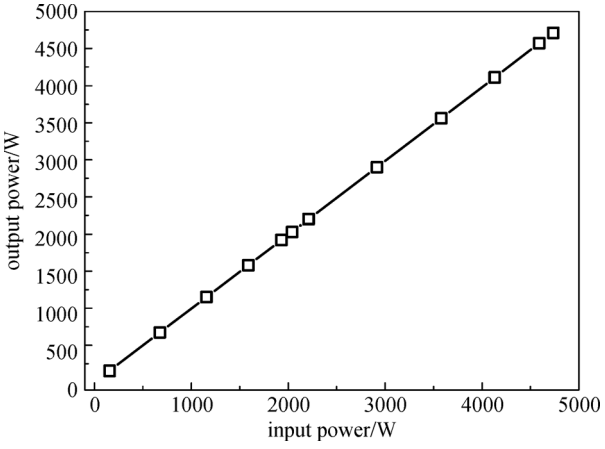

Fig. 9 Output power of 7×1 combiner versus pumping power

4 Conclusions

In this paper, we have carried out the development and the performance test of the 3×1 and 7×1 TFB end-pumping combiner. The results, with the power handling capacity being 2.11 and 4.72 kW and the average coupling efficiency being 95.1% and 99.4% for 3×1 and 7×1 combiner, respectively, indicates a high maturity of coupling manufacturing procedure and marks the best performance reported to date, paving the path for the further development of high power fiber laser.

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References

1. Grudinin B D N P, Turner P W, Nilsson L J A, Zervas M N, Ibsen M, Durkin M K. Multi-fibre arrangements for high power fibre lasers and amplifiers. U.S. Patent 6826335, 2004
2. Wang D, Wang Y, Liu S, Ma X. New reflecting side-pumped method of double-clad fiber laser by micro-prism. Acta Optica Sinica, 2009, 29(4): 974–979
3. Sean W M, Koplow J P, Hansen A. Embedded-mirror side-pumping of double-clad fiber lasers and amplifiers. In: Proceedings of Conference on Lasers and Electro-Optics/Quantum Electronics and Laser Science Conference and Photonic Applications Systems Technologies, 2008
4. Ripin D J, Goldberg L. High efficiency side-coupling of light into optical fibres using imbedded V-grooves. Electronics Letters, 1995, 31(25): 2204–2205
5. Xiao Q, Yan P, Yin S, Hao J, Gong M. 100 W ytterbium-doped monolithic fiber laser with fused angle-polished side-pumping configuration. Laser Physics Letters, 2011, 8(2): 125–129
6. Huang C W, Chang C L, Jheng D Y, Hsu K Y, Huang S L, Huang D W. Direct side pumping of double-clad fiber laser by laser diode array through the use of subwavelength grating coupler. IEEE Photonics Journal, 2012, 4(2): 411–421
7. Xiao Q, Yan P, Ren H, Chen X, Gong M. A side-pump coupler with refractive index valley configuration for fiber lasers and amplifiers. Journal of Lightwave Technology, 2013, 31(16): 3015–3022
8. Kopp V I, Park J, Wlodawski M. Polarization maintaining, high-power and high-efficiency (6 + 1)×1 pump/signal combiner. In: Proceedings of SPIE 8961, Fiber Lasers XI: Technology, Systems, and Applications. 2014, 89612N
9. Wetter A, Faucher M, Lovelady M, Séguin F. Tapered fused-bundle splitter capable of 1 kW CW operation. In: Proceedings of the Society for Photo-Instrumentation Engineers. 2007, 64530I
10. Xiao Q, Yan P, He J, Wang Y, Zhang X, Gong M. Tapered fused fiber bundle coupler capable of 1 kW laser combining and 300 W laser splitting. Laser Physics, 2011, 21(8): 1415–1419
11. Xiao Q, Ren H, Chen X, Yan P, Gong M. Tapered fiber bundle 7 × 1 end-pumping coupler capable of high power CW operation. IEEE Photonics Technology Letters, 2013, 25(24): 2442–2445
12. Zhou H, Chen Z, Zhou X, Hou J, Chen J. All-fiber 7×1 pump combiner for high power fiber laser. Optics Communications, 2015, 347: 137–140

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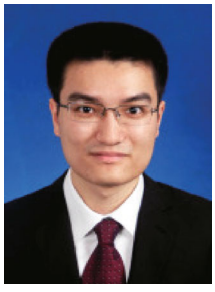

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