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All-fiber 7 × 1 pump combiner for high power fiber laser

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ABSTRACT

We investigate $N \times 1$ pump coupler theoretically and experimentally. Firstly the influence of lengths of the transitional region and the waist region of tapered fiber bundle on the efficiency of a 7×1 pump combiner is numerically analyzed. The results suggest that there is a minimum length for the transitional region in order to achieve high efficiency; meanwhile, the waist region should be as short as possible. Then a 7×1 pump combiner is fabricated. The transmission efficiencies of all 7 ports are higher than 98% and the final total output power is as high as 3.81 kW with 98.4% transmission efficiency. This is the highest output power reported to date and improvement further is possible by better cleaving, splicing and using LD with higher power. The experimental result verifies the simulation which can be applied in the fabrication of $N \times 1$ pump combiners.

1. Introduction

The outstanding performance of fiber lasers and their attractive advantages, including excellent beam quality, compactness, high transmission efficiency, and low maintenance, have facilitated extensive applications of fiber lasers in industry, biology, medicine, and other areas [1]. Nowadays, fiber lasers have emitted kilowatt power [2–4] and generally high power fiber lasers and fiber amplifiers adopt double-clad doped fibers. Thus how to couple the pump light into the inner clad of the double-clad doped fiber efficiently is pivotal for high power fiber laser output.

Generally, pump coupling techniques can be characterized as side-pumping [5,6] and end-pumping. Side-pumping is coupling the pump light into the inner clad from the side face, which can be achieved through, for example, the GT-Wave technology [7], the embedded mirror method [8], the V-groove side coupling technique [9], the embedded lens method [10], the fiber angle polished method [11], the side grating coupler [12], and so on. End pumping means coupling the pump light into the inner clad through one or two end faces of the fiber, normally based on tapered fiber bundle (TFB). TFB is the main method to fabricate high power fiber combiner considering the coupling efficiency, heat dissipation, package and manufacture techniques of high power devices. According to the applications, combiners manufactured by TFB can be divided into two kinds: $(N+1) \times 1$ combiners with one signal fiber in the bundle center and $N \times 1$ combiners without signal fibers. N pump sources and signal source are coupled into one double-clad fiber through a $(N+1) \times 1$ combiner which is applied into fiber amplifiers to improve the power of fiber laser. $N \times 1$ combiners are utilized to combine the pump power through coupling N high power multi-mode fibers into one multimode fiber. Due to the approximate circular structure of the cross section, 7×1 combiners are easier to be spliced and have lower insert loss which makes them more suitable for high power fiber lasers compared with 3×1 combiners and 4×1 combiners. Low insertion loss leads to less thermal accumulation at the splice point and the damage threshold of the device is higher.

In 2006, Ref. [13] reported a combiner which delivered 1 kW of total output power with 0.2 dB insertion loss. At present, ITF lab provides commercial combiners with total pump input power of 1.2 kW and 760 W for $(N+1) \times 1$ and $N \times 1$ configurations, respectively [14]. Yu et al. demonstrated an Yb-doped fiber laser, achieving 1.2 kW output power. In this system, the pump power was combined using a 19×1 fused-fiber combiner with a measured loss of $< 1\%$, providing a nominal pump power of 2.0 kW [15]. In 2013, a high efficiency tapered fiber bundle 7×1 end-pumping coupler with a handle pumping power of 3.01 kW was reported [16].

With the elevation of the output power of the fiber laser, the requirement of power support capability of fiber combiner is increasingly higher. Especially at the kilowatt level, the support power depends on loss directly and only very tiny loss can support more than kilowatt power transmission. The TFB technique has been developed for many years, and we have known that all the cores of input fibers should be tapered into the range of output fiber core. However, how to confirm the lengths of every sections of the taper region and the influence of the lengths on

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transmission efficiency are still not clear. Correlate theoretical analyses have not been reported. At present, it is also important to manufacture combiner that can stand for several kW in high power fiber laser.

In this paper, we carry out theoretical and experimental investigations of 7×1 pump combiner focusing on the transmission efficiency. The influence of transitional region length and waist length on the transmission efficiency of pump combiner is numerically analyzed and finally an optimum structure of pump combiner for high efficiency is designed. Based on the theoretical study, 7×1 pump combiner with high efficiency is manufactured and 3.81 kW output power is obtained with 98% transmission efficiency. To the best of our knowledge, the presented combiner delivers the highest pump power obtained from any pump combiner.

2. Theoretical analysis

$N \times 1$ combiner based on TFB technique is fabricated through three steps including tapering, cleaving and splicing. Among the three steps the most important one is tapering the fiber bundle. In this process the structure of the centro-symmetric array of the fiber bundle and the lengths of every sections of the TFB are two factors to be considered carefully. Thus in order to reduce the transmission loss of the fiber combiner, reasonable structure of the fiber combiner and perfect operation in the three phases (tapering, cleaving and splicing) of the manufacture are required.

The centrosymmetric arrayed structure of N pump fibers is maintained by inserting N pump fibers into a capillary with suitable inner diameter as shown in Fig. 1. The input fibers and the output fiber should be chose to ensure the match of numerical aperture (NA). The NA of input fiber will be increased along the taper region; if the NA of input fiber at the final end-face is larger than that of the output fiber, the transmission efficiency will be lowered down. The lengths of the transitional region and the waist region of the TFB can affect the transmission efficiency of the fiber combiner directly. Ultra-long or ultra-short length will lead to low efficiency, resulting in accumulation of a large amount of heat at the splicing point of the TFB and the output fiber. Therefore, in the process of tapering, proper lengths of each tapering regions should be chosen to satisfy two fundamental principles which are brightness conservation and adiabatic tapering [17,18].

One of the decisive factors for the transmission efficiency of a combiner is whether the brightness is conserved during the evolution from the N input laser beams to the output laser beam. The brightness conservation can be described by the ratio of integrated brightness of the total input of a combiner to the integrated brightness of the output which can be expressed as:

$$D_{out}^2 \mathrm{NA}_{out}^2 \geq N \times D_{in}^2 \mathrm{NA}_{in}^2$$

where NA_{in} and NA_{out} are the NA of the input and output fibers; D_{in} and D_{out} are the core diameters of the input and output fibers, respectively; and N is the number of input fibers.

In this paper, the input pump fibers are seven multimode fibers with 220 and 242 μm (NA=0.22) core and clad diameters,

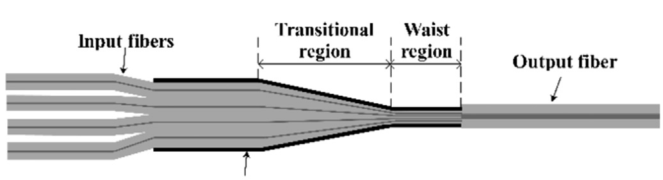

Fig. 1. The schematic diagram of $N \times 1$ combiner.

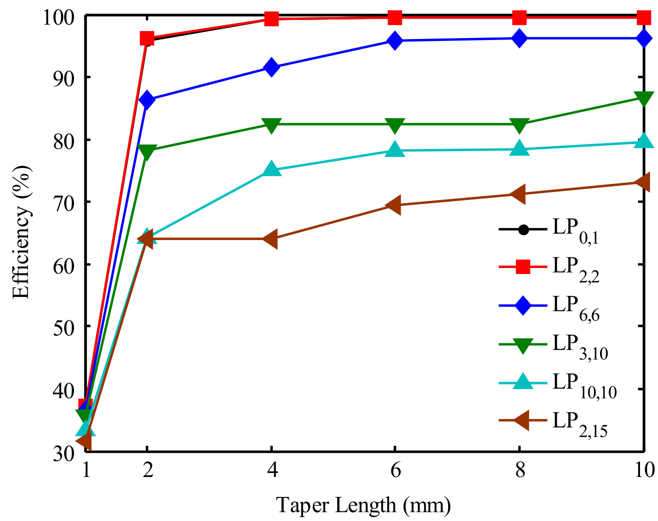

Fig. 2. Efficiencies of multiple modes versus taper length.

respectively, and the output fiber is a double cladding fiber with 20 and 400 μm (NA=0.46) core and clad diameters. According to the fiber parameters used, $400^2 \times 0.46^2 \geq 7 \times 220^2 \times 0.22^2$, so the transmission efficiency can approach 100%. In addition, transmission efficiency is also affected by other factors (such as the length of the taper). Finite difference beam propagation method (FD-BPM) is used to numerically calculate the propagating energy along the axial orientation of combiner. FD-BPM was presented by Hermansson in 1989 [19,20]. It divides the waveguide cross section into many squares, and amplitudes in each square are calculated by the difference equation with boundary conditions, so we can get the amplitude distribution of the whole cross section and the whole waveguide. FD-BPM is one of the most effective computational tools for analyzing the structure of a complex optical waveguide. In the simulation, the lateral computing step is 1 μm, the axial computing step is 5 μm.

Transmission efficiencies of 6 modes including the fundamental $LP_{0,1}$ mode as well as higher order modes $LP_{2,2}$, $LP_{2,15}$, $LP_{3,10}$, $LP_{6,6}$ and $LP_{10,10}$ are calculated as an example to study the relationship between the transmission efficiency and the taper length. The result is shown in Fig. 2. From Fig. 2, the coupling efficiency of a low-order mode is higher than that of a higher-order mode. On the other hand, as the taper length increases, the efficiencies of each mode begin to saturate, and the efficiency of most of the modes begins to stabilize when the taper length is over 8 mm. Especially low-order mode has no loss in this case. Low-order modes are confined easily by the fiber core, thus with 8 mm taper length there is almost no loss for $LP_{0,1}$ and $LP_{2,2}$ mode. It is difficult for the fiber core to confine high-order modes, and because the fiber is tapered, high-order modes will leak into the cladding. Although the taper is lengthened the transmission efficiencies of $LP_{2,15}$ and $LP_{10,10}$ are just about 70% and this value is a saturated one. Considering the low proportion of high-order modes in the output light, the high loss of high-order modes will have little influence on the total transmission efficiency.

Besides the length of transitional region, the length of the tapering waist region is another key parameter affecting the efficiency of the fiber combiner. In the same way, with a fixed length (10 mm) of the tapering region, the transmission efficiencies of $LP_{0,1}$, $LP_{3,3}$ and $LP_{10,10}$ modes are calculated for different lengths of tapering waist regions, namely 0, 2, 4, 6 and 8 mm. The results are illustrated in Fig. 3. It can be found that the transmission efficiency is improved with shorter waist region. Especially for higher-order mode, the transmission efficiency decreases drastically with the

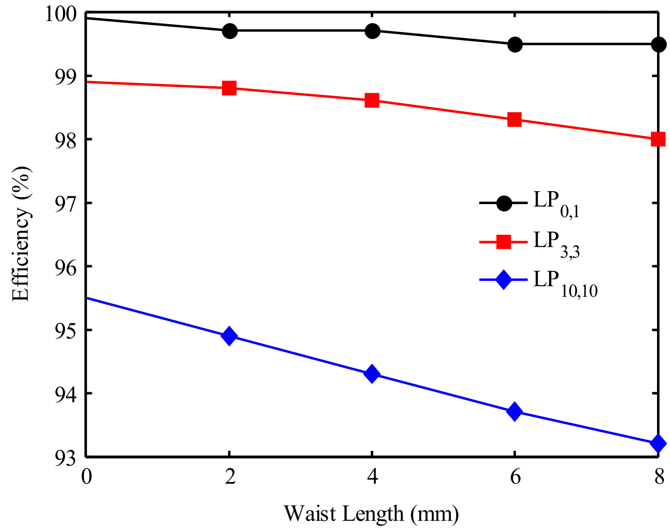

Fig. 3. Efficiencies of different modes of combiner versus waist length.

increase in the length of the waist region. Consequently, to reduce the transmission loss, the cleave position should be in the intersection of transitional region and waist region to shorten the waist region, which requires very careful handling and makes the fabrication of high-efficiency high-power fiber combiner difficult.

3. Experiment

The structure parameters of high efficiency combiner are obtained through simulation. Based on the simulation results, 7×1 pump combiner is fabricated and the power capability and efficiency are measured. The fabrication process can be divided into four steps, bundle, taper, cleave and splice. Firstly, 7 fibers with core/inner clad diameter 220/242 μm are arrayed side by side and then inserted into one capillary with suitable inner diameter to maintain the array. Then this bundle confined by the capillary is tapered under clear fire source. The diameter of the tapered bundle should match the output fiber and the lengths of each section of the tapering region are chosen according to the simulated results. In the next step, the TFB is cleaved at a suitable point to make the waist region as short as possible. Finally, the TFB is spliced with an output fiber with a core/inner clad diameter of 20/400 μm. The cross-section of the end-face of the TFB and the side view of the splice are shown in Fig. 4.

A laser diode (LD) at 976 nm with an output power of 400 W is used to measure the transmission efficiency of the fabricated combiner. Transmission efficiencies of 7 ports are almost the same. For different power levels, the average efficiencies are 97.8%, 98.2%, 98.5%, 98.3%, 98.4%, 98.6%, 98.5%, 98.5%, 98.4% and 98.7% as shown in Fig. 5. Most of the power is contained in the fundamental mode, therefore the efficiency is close to unity as shown in Fig. 2.

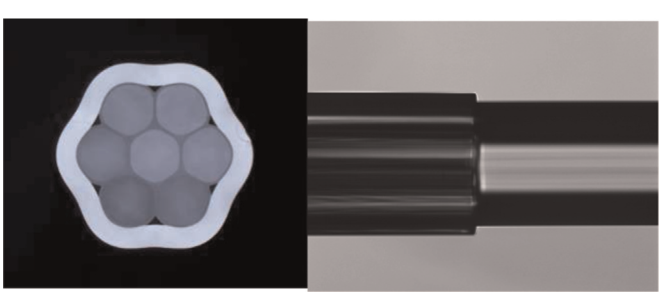

Fig. 4. Cross-section of the end-face of the TFB and side view of the splice.

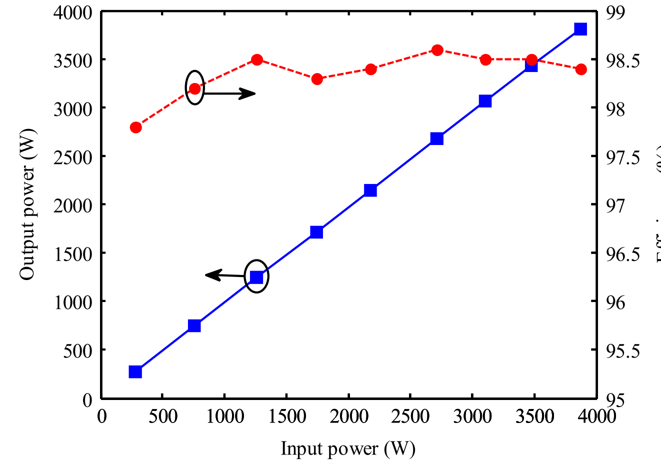

Fig. 5. The output power (squares and line) and corresponding efficiency (dots and dotted line) of combiner versus the total input power.

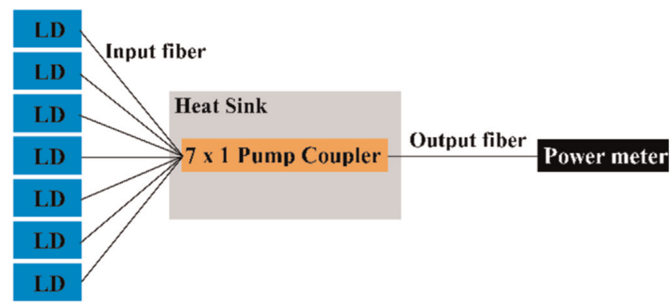

Fig. 6. Schematic of the experimental setup for testing the power scalability of the combiner.

Additionally, the power capability is measured and the measurement system is depicted in Fig. 6. The Pump source is composed of six 600 W LDs and one 400 W LD. These 7 LDs are spliced with the 7 pump fibers of the combiner and then the combiner is mounted on a heat sink. The operation current is increased to 8.5 A corresponding to a total output power 3.87 kW. The measured output power of the fiber combiner is 3.81 kW and the calculated efficiency is 98.4%. An image of the experiment is shown in Fig. 7. Operating under this level of power for long time, tens of watts power must be lost even for fiber combiners with such a high efficiency. Therefore heat dissipation is very important.

4. Conclusion

In this paper, we have numerically analyzed the influence of the lengths of transitional region and waist of TFB on the efficiency of a 7×1 pump combiner under the condition of fundamental mode propagation in the combiner. The results suggest that based on the satisfaction of brightness conservation, there is a minimum length for the transitional region in order to achieve high efficiency; meanwhile, the waist region should be as short as possible. Under this condition, the combiner has theoretically negligible loss for fundamental modes propagation. Based on the simulation result, a high-efficiency 7×1 pump combiner has been successfully fabricated. The transmission efficiencies of all 7 ports are higher than 98% and the final total output power is as high as 3.81 kW with 98.4% transmission efficiency. The experimental result verifies the simulation which can be applied in the fabrication of $N \times 1$ pump combiners.

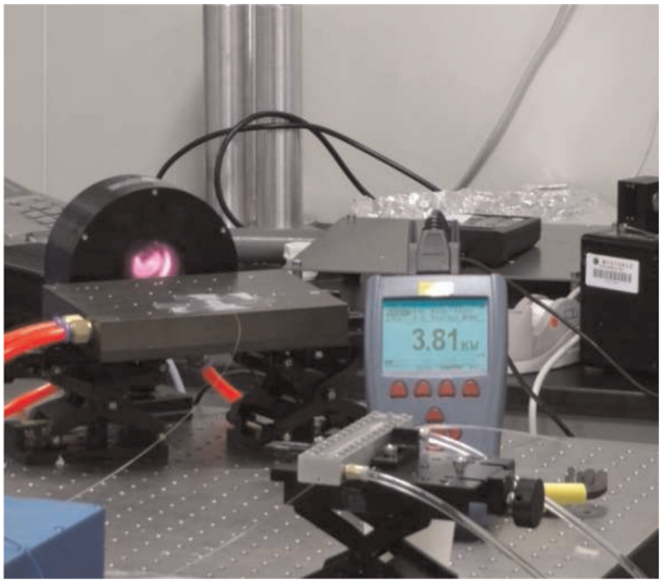

Fig. 7. Image showing the power characterization with 3.81 kW total output power achieved.

Acknowledgments

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