High Efficiency Pump Combiner Fabricated by CO_2 Laser Splicing System

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ABSTRACT

High power combiners are of great interest for high power fiber lasers and fiber amplifiers. With the advent of CO_2 laser splicing system, power combiners are made possible with low manufacturing cost, low loss, high reliability and high performance. Traditionally fiber optical components are fabricated with flame torch, electrode arc discharge or filament heater. However, these methods can easily leave contamination on the fiber, resulting inconsistent performance or even catching fire in high power operations. The electrodes or filaments also degrade rapidly during the combiner manufacturing process. The rapid degradation will lead to extensive maintenance, making it unpractical or uneconomic for volume production. By contrast, CO_2 laser is the cleanest heating source which provides reliable and repeatable process for fabricating fiber optic components including high power combiners.

In this paper we present an all fiber end pumped 7x1 pump combiner fabricated by CO_2 laser splicing system. The input pump fibers are 105/125 (core/clad diameters in μm) fibers with a core NA of 0.22. The output fiber is a 300/320 fiber with a core NA of 0.22. The average efficiency is 99.4% with all seven ports more than 99%. The process is contamination-free and highly repeatable. To our best knowledge, this is the first report in the literature on power combiners fabricated by CO_2 laser splicing system. It also has the highest reported efficiency of its kind.

Keywords: Pump combiner, CO_2 laser splicer, fiber optic component, tapered fiber bundle, fiber laser

1. INTRODUCTION

Fiber lasers have attracted great attention in recent years due to its high efficiency, simplicity, low cost, maintenance-free, compactness, and excellent beam quality, etc. In the past decade, the output power of fiber lasers has been scaled up to multi-kW or even 100-kW level. [1] However, due to the relative low power of a diode pump laser, the output power of single fiber laser is limited. Therefore the availability of power combiners is essential to the development of high power fiber lasers. In recent years multi-kW power combiners have been reported with either side-pump or end-pump schemes. Nevertheless, these combiners are usually fabricated with gas flame, electrode arc discharge or filament heater. While these well-established methods are proved to be reliable in some conventional splicing, they show significant drawbacks in long-time tapering process compared with CO_2 laser. [2-3] Flame is the first established method for fiber heating and it is generally preferred for fabricating tapered fiber bundles such as combiners and couplers since it can produce a relatively wide heating zone which leads to smooth tapers with low loss and minimal ripples. However, it requires sustainable gas supply which may cause safety issues. In the past few decades, electrode arc discharge has largely replaced the flame in fiber fusion splicing. It is fully automated, almost operator independent and safer than flame. The narrow heating zone is ideal for precision fiber fusion splicing but becomes very inefficient when it comes to large diameter fibers or tapered fiber bundles. Electrode cleaning and calibration are usually required after making a combiner as it may take a few minutes of heating time. The electrodes can get worn rapidly resulting in unrepeatable processes and unpredictable performance. The narrow heating zone could also lead to large ripples and high loss. Filament is an alternative heating element for manufacturing power combiners. The interchangeable filament can accommodate fibers with a variety of diameters but it requires argon gas supply for operation. The filament may also deposit on the fiber which can cause failure or even catch fire in high power operations. The short lifetime of the filament also leads to high operation cost in the long run.

By contrast, CO_2 laser is the cleanest heating source which leaves no deposits on the fiber and requires little maintenance. It does not have any operation consumable cost. The interchangeable lens option can also provide wide or narrow heating zone depending on different applications. Table 1 lists the advantages and disadvantages of different heating methods in fabricating power combiners. [2-3]

METHOD	FLAME TORCH	ELECTRODE ARC DISCHARGE	FILAMENT HEATER	CO_2 LASER
Pros	Wide heating zone (~5 mm)	Low initial cost; No need for gas supply	Concentric heat source; Interchangeable filament	Cleanest with no deposits on fibers; No consumable cost; Wide or narrow heating zone
Cons	Need gas supply; Safety concerns	Need to clean electrodes often for large fibers; Deposit on fibers when electrodes are not clean	Need Argon for filament protection; Filament deposits on fiber; Time consuming filament alignment	Requires sophisticated power feedback control
Lifetime of heating elements (assuming six minutes heating time to make a combiner)	N/A (consuming gas, burner tips, etc. in operations)	2 hours; Good for 20 combiners	1 hour; Good for 10 combiners	20,000 hours; Good for 200,000 combiners

Table 1 — Comparison of different heating methods in fabricating combiners

2. FABRICATION OF END-PUMPED COMBINERS

2.1 Theoretical Analysis

The schematic diagram of a 7x1 pump combiner is shown in Figure 1. The seven fibers are inserted to the capillary tube and tapered together then spliced to the output fiber. To achieve high transmission efficiency, the brightness conservation must be met. The brightness conservation can be expressed by integrated brightness of the total input and the integrated brightness of the output as below [4]

$$nD_{in}^2 NA_{in}^2 \leq D_{out}^2 NA_{out}^2 \quad (1)$$

Where n is the total number of input fibers. Typically n can be expressed as

$$n = 6 \times \sum_{i=1}^{m} i + 1 \tag{2}$$

(i =1, 2, 3…,n=7, 19, 37…). These numbers will ensure a compact hexagonal packing of input fibers. D_{in}, NA_{in} are the diameter and the numerical aperture (NA) of the input fiber; D_{out}, NA_{out} are the diameter and the NA of the output fiber. In this paper, n=7 and the input fibers are 105/125/0.22 (core diameter/clad diameter in µm/NA) multimode fibers and the output fiber is a 300/320/0.22 multimode fiber. $7 \times 105^2 \times 0.22^2 < 300^2 \times 0.22^2$ so the brightness conservation is satisfied and the transmission efficiency can approach 100% ideally.

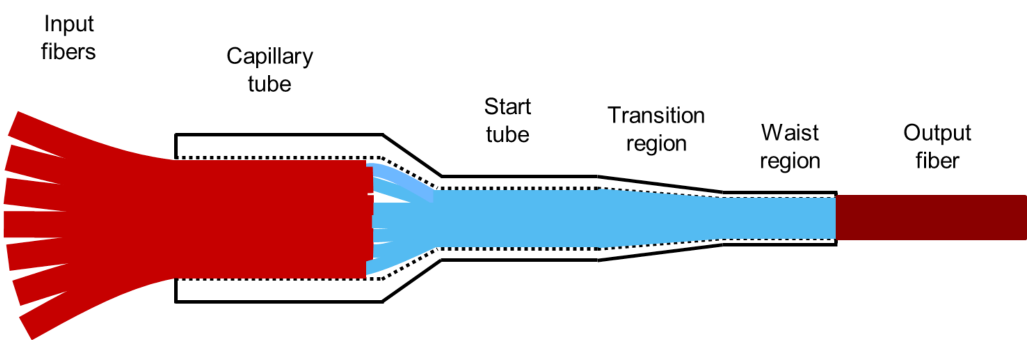

Figure 1 — The schematic diagram of a 7x1 pump combiner

2.2 Combiner fabrication

The fabrication of end-pumped combiner includes the following steps:

- Strip off the acrylate coating of seven input fibers for certain distance and clean them until no debris left.
- A capillary tube is tapered to a start tube with CO_2 laser splicer LZM-100. The start tube should have an inner diameter (ID) that just fits seven input fibers. In this case the ID should be a little larger than 375 µm to ensure a compact hexagonal packing of the seven-fiber bundle.
- The seven fibers are inserted to the start tube and form a hexagonal-packed bundle.
- Taper the start tube with CO_2 laser splicer until the core-to-core size in the waist region of the tapered fiber bundle matches or is a little less than the core size of the output fiber. For this pump combiner the core-to-core diameter of the final tapered bundle is about 290 µm to allow some alignment tolerance during the final combiner splicing.
- The tapered bundle is then cleaved by a Fujikura CT-105 Fiber Cleaver at the waist region. Figure 2 shows the end face of the final tapered fiber bundle after cleaving.
- Splice the cleaved tapered fiber bundle to the output fiber with CO_2 laser splicer. The LZM-100 is equipped with interchangeable lens options which can provide wide or narrow heating zones based on different application. Generally speaking wide heating zone is preferred for fabricating tapered fiber bundles while narrow heating zone is more suitable for precision fiber splicing. Figure 3 is the side view of the splice between the tapered fiber bundle and the output fiber. The slightly rounded edge provides good splice strength while the transmission efficiency is also uncompromised.

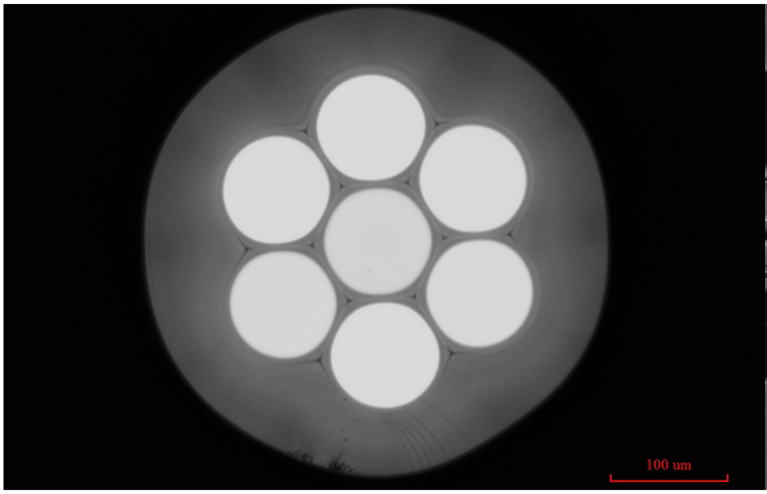

Figure 2 — The final end face of the tapered seven-fiber bundle. The diameter formed by the seven input fiber cores is about 290 μm while the core diameter of the output fiber is 300 μm.

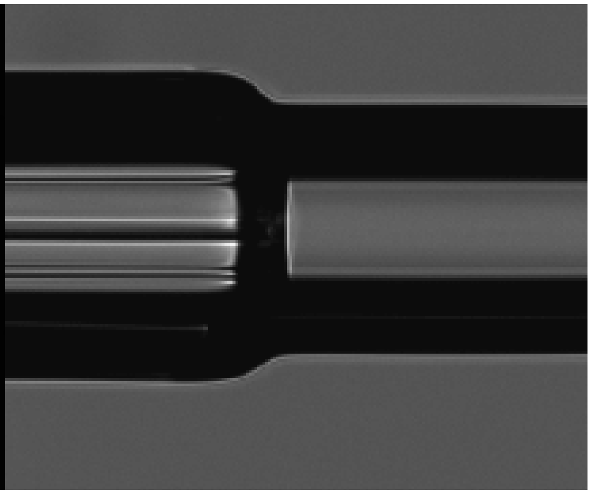

Figure 3 — The side view of the splice between the tapered fiber bundle and the output fiber. The left side is the tapered fiber bundle and the right side is the output fiber.

It is worth mentioning the combiner fabrication process is very repeatable. We fabricated a few combiners with the same process and all of them had very similar performance. The CO_2 laser splicer does not have any consumable parts and does not need cleaning or calibration service during operation, making it ideal for high volume combiner production.

3. COMBINER PERFORMANCE

The schematic of the experimental setup for measuring the combiner efficiency is shown in Figure 4. Due to the limitation of testing equipment, only one input port was spliced to the laser diode (LD) and tested each time. The pump source is a 140 W continuous wave (CW) LD operating around 915 nm. A fan-cooled power meter was used to measure the input and output powers.

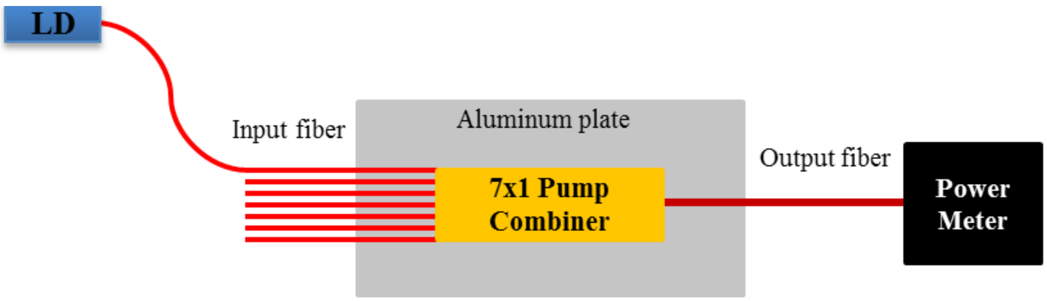

Figure 4 — The schematic of experimental setup for measuring the efficiency of the 7x1 pump combiner.

We tested the combiner up to about 50 W. Figure 5 shows the thermal image and the real image of the combiner after running for 30 minutes at 50 W. The measured transmission efficiencies of each input port are shown in Table 2. The transmission efficiencies are almost identical for all 7 ports with an average efficiency of 99.4%. It is also worth mentioning that even without any active cooling method, the temperature of the combiner still remains around the room temperature after about 30 minutes operation. The highest temperature on the combiner is close to the splice point which is about 24°C, corresponding to only 1-2°C of temperature increase.

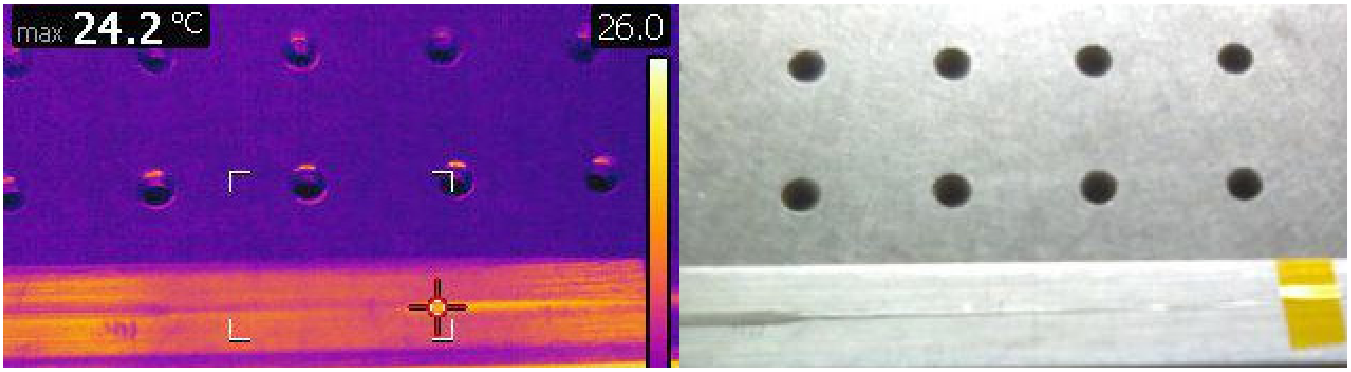

Figure 5 — The thermal image (left) and the real image (right) of the 7x1 pump combiner.

PORT #	INPUT POWER (W)	OUTPUT POWER (W)	EFFICIENCY (%)	LOSS (dB)
1	51.3	50.9	99.2	0.03
2	51.3	50.9	99.2	0.03
3	51.3	50.9	99.2	0.03
4	51.3	51.0	99.4	0.03
5	51.3	51.1	99.6	0.02
6	51.3	51.2	99.8	0.01
7	51.3	51.0	99.4	0.03
Avg	51.3	51.0	99.4	0.03

Table 2 — The transmission efficiencies of each input of the pump combiner

4. CONCLUSION

In this paper we discussed the advantages of CO_2 laser splicer in fabricating combiners and an all fiber end pumped 7x1 pump combiner was made and tested. An average efficiency of 99.4% with all seven inputs more than 99% were obtained from the pump combiner. The combiner generated little temperature change during operation even without any active cooling method. The fabricating process is also very repeatable without introducing any degradation or contamination during operation. This new method with CO_2 laser splicer provides a very good alternative for manufacturing power combiners, especially in large volume.

ACKNOWLEDGEMENT

The author would like to acknowledge Wenxin Zheng for helpful discussions and conceptual work on the power combiners. The author would also like to thank Brad Hendrix and Al Swanson for proofreading the paper.

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