

# High-power fiber laser combination technology

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**Abstract** Research on fiber laser combination is discussed briefly in this paper. High-power double clad-fiber laser beam combination technology is introduced and different kinds of fiber laser beam combination and coherent combination technologies are evaluated. Tapered fused bundle (TFB) couplers are used in laser combine for higher power. In this paper, the theory and progress in TFB coupling are introduced. The experiment on our self-fabricated TFB is presented. The efficiency of the fiber coupler exceeded 70% and increased as the input power went up. A maximum total output power of 689 W was obtained, with an efficiency of 74%. The fiber coupler displayed stability during the course of the experiment, without any cooling provided.

**Keywords** fiber laser, combination technology, fiber coupler, tapered fused bundle (TFB), fabrication

## 1 Introduction

High-power fiber lasers have unique characteristics and have developed rapidly in recent years. The output of continuous wave (CW) power can now achieve 2 kW in a single fiber laser by using large diameter double clad fibers. Since larger than 10 kW CW output power is needed in industries and military fields, laser beam combination technology is researched in many institutes and military organizations.

The Northrop Grumman Company of the USA presented the master oscillator power amplifier (MOPA) technique in 2003 (shown in Fig. 1) that achieved 470 W CW output power and in 2006, 4 fiber laser coherence beam combination was achieved. Typically, the master oscillator is a single mode laser running at relatively low

power. The master oscillator serves as a seed laser for the power amplifier that boosts the signal. MOPA configurations are often preferred for lasers with narrow line-width since it is easier to control the line-width via the low power master oscillator than it is for a single high power laser cavity. The signal beam splitter and phase modulation are employed ( $\Phi$  mod/beam splitter).

### 1.1 Spectral combining

For spectral combining [1–4], multiple single mode lasers at different wavelengths are combined into a single beam path. Promising results for efficient, high power combining have been demonstrated at the University of Central Florida in USA, using so-called volume Bragg gratings (VBGs) written into photo-thermorefractive glass. Figure 2 outlines this principle, where multiple lasers at different wavelengths are focused to a VBG. The VBG diffracts the incoming beams at different angles and that can, therefore, exit the VBG in a single beam path. Efficient combining coupled with proper alignment of the lasers with VBG requires as little divergence of the input beams as possible and stable lasing wavelength with as narrow line-width as possible. Line-widths of around 100 pm allow for high diffraction efficiency and therefore efficient combining. Hence, fiber lasers that can provide wavelength-stable, fundamental mode operation with highest possible power with such a line-width are the best choice for spectral beam combining.

### 1.2 Coherent combining

Coherent combining relies on multiple phase-locked single-mode laser beams. A single laser seeds an array of fiber amplifiers [5–10]. Output beams from the amplifiers have similar wavelengths and can be combined with high efficiency if the output beams are in phase. Hence, polarization control and line-width control are required. Various schemes for realizing phase-locking have been

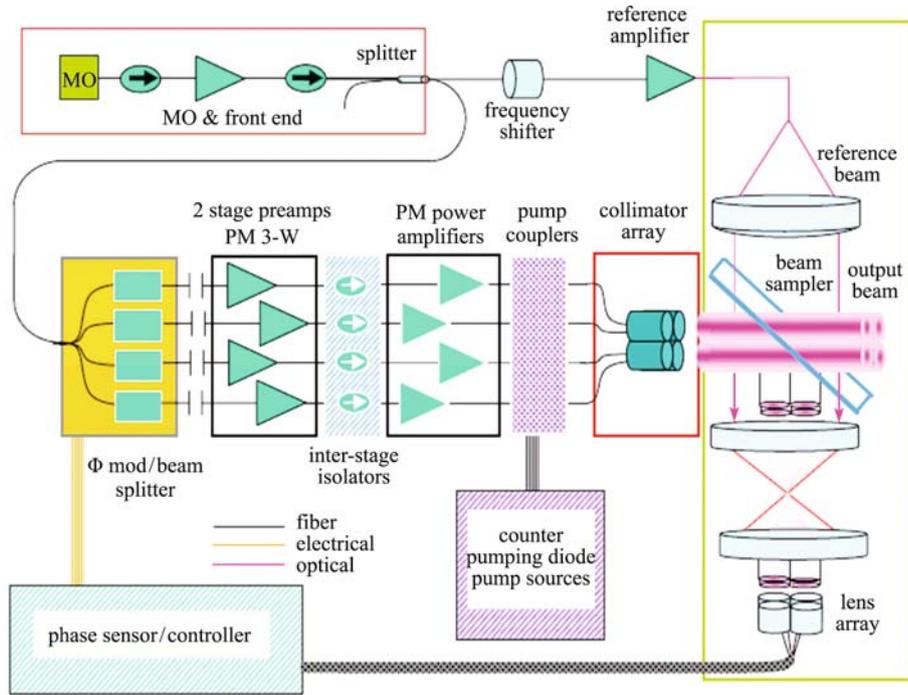


Fig. 1 Master oscillator power amplifier

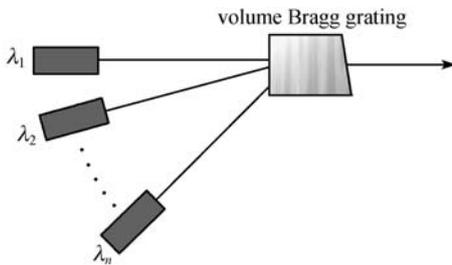


Fig. 2 Schematic illustration of spectral beam combining using volume Bragg grating

proposed, including passive combining. Line-width control is important, as line-width sets the path length matching requirements for all of the separate beams. Hence, the broader the line-width the closer one has to match the path lengths. Another critical factor is possible introduction of phase noise during amplification. Hence, it is desired to push the power capacity of the individual lasers to as high power levels as possible while maintaining narrow line-width and stable polarization.

### 1.3 Fiber laser beam combination

Compared with MOPA and spectrum coherent combine, the method which use the passive device—the tapered fused bundle (TFB) coupler promises high reliability and

flexibility, though it means worse beam quality and difficulties in heat handling.

The 200 W power handling has been demonstrated in 2005 [11] by the ITF group. They demonstrated their findings on the TFB  $1 \times 7$  splitter using a 1.00 mm core diameter, 0.22 numerical aperture (NA) input fiber coupled with seven 400 micron core, 0.22 NA output fibers, that were tested up to 860 W at 976 nm [12]. The TFB device has, so far, passed high power operation standards [13,14].

## 2 Fabrication and experiment

The  $7 \times 1$  combiner configuration was selected for this purpose since it is symmetrical and easy to process. Multimode fibers with diameters ranging from 400/480  $\mu\text{m}$  were chosen for the fabrication since they are more suitable for high power operation.

First, the coat was removed carefully to make sure the fiber is flawless. Then seven fibers were bound symmetrically with appropriate clamp. The flaws and impurities can become the defects which may cause severe damage to the device [15].

The finished bundle was fixed in the tapering apparatus [16,17] that is designed as an electronically controlled tapering device equipped with a movable gas burner and two fiber holders.

The gases, pure hydrogen, and pure oxygen were mixed in controllable ratio and drove to the burner. Gas-pressure

regulators and flowmeters were used to control the flows of these gases [18,19].

Several stepping motors used in the system provide enough flexibility for processing the adjustment, including the rotation of two holders which is important to combine the separate fibers while tapering.

Reverse tapering was employed, which means that the flame and pulling holder move toward opposite directions. The fabrication platform is shown as Fig. 3.

The temperature and the heating areas are determined by the gas flux, and the stretching velocity and the rotation velocity of the holders reflect on the result altogether. Many parameters were tested. The cross-section of both prepared fiber bundle and the tapered section are shown in Fig. 4.

So far, the ideal TFB have the following characteristics: taper length is 15 mm; max diameter of output surface is about 540  $\mu\text{m}$ ; well combined with no flaws.

Then 5 routes of 7 were chosen randomly for the high power experiment, limited by the number of sources.

The 5 fiber laser beam combination experiment is shown in Fig. 5. Five independent fiber lasers were coupled into the 7 $\times$ 1 fiber coupler. The regular end pumped fiber laser

system was employed in this experiment including a laser diode (LD), dichroic mirror, and Yb-doped fiber (YDF). High-powered LDs with 975 nm wavelengths were used in each single configuration. The maximum output for 4 LDs is 300 W, and an output of 100 W measured for each, limited solely by experiment conditions. The dichroic mirror has a reflection rate of 1080 nm and transmittance rate at 975 nm. The Yb-doped fibers have the following characteristics: 15 m long; 20  $\mu\text{m}$  and 400  $\mu\text{m}$  for core diameter and cladding, respectively; NA of 0.22; and absorption efficiency of 3 dB/m.

### 3 Results

The results are presented in Table 1 as follows. Optical-to-optical efficiency of each fiber laser was around 50%. The efficiency of fiber coupler exceeded 70% and increased as the input power went up. The maximum total output power of 689 W was obtained, and 74% efficiency was achieved at the same time. The result is shown in Fig. 6.

Further, the fiber coupler displayed stability during the experiment without any need for cooling.

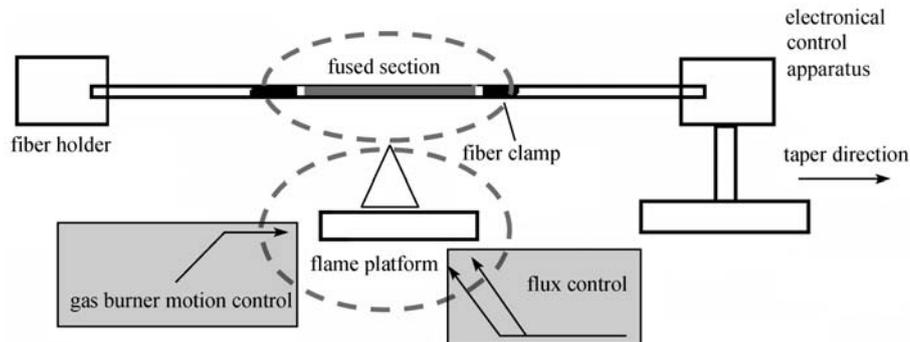


Fig. 3 Configuration of taper apparatus

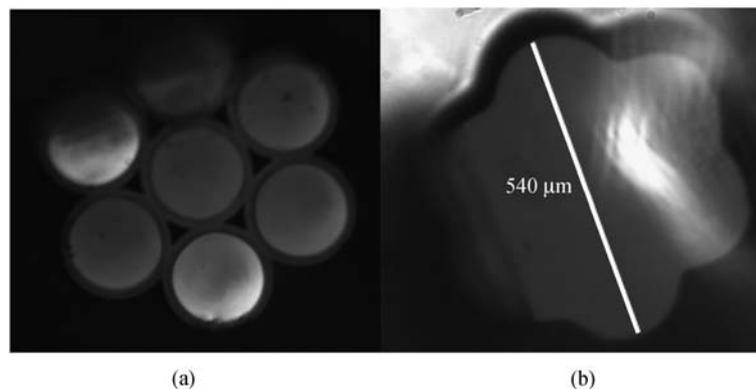


Fig. 4 (a) Cross section of fiber bundle; (b) cross section of tapered section, diameter is measured as 540  $\mu\text{m}$

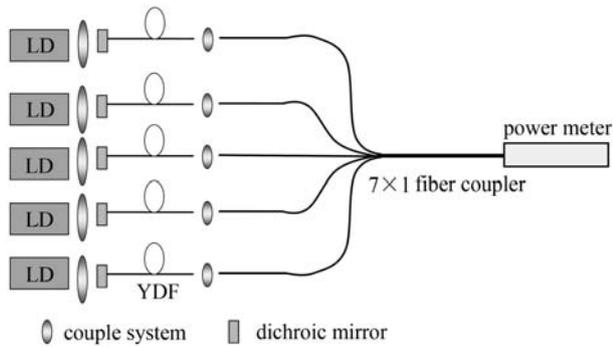


Fig. 5 Five fiber lasers beam combination

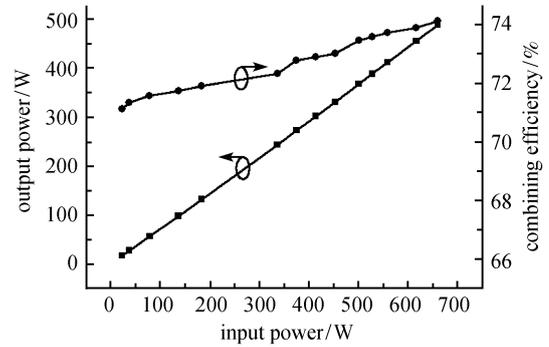


Fig. 6 Combining efficiency

Table 1 Efficiency of 5 fiber lasers beam combination

fiber laser 1 output/W	fiber laser 2 output/W	fiber laser 3 output/W	fiber laser 4 output/W	fiber laser 5 output/W	total output/W	output after beam combination/W	efficiency/%
4.4	4.6	4.3	7.0	3.3	23.5	16.7	71.12
7.2	7.0	7.3	11.0	4.7	37.8	27.0	71.34
12.4	14.1	16.8	22.1	13.6	79.2	56.7	71.56
24.7	26.0	30.2	37.8	18.3	136.9	98.2	71.72
34.0	36.4	40.0	50.1	23.4	183.6	132.1	71.89
68.9	69.5	77.8	67.7	32.6	336.6	243.4	72.32
77.5	77.9	85.7	98.3	36.0	375.3	273.1	72.76
86.3	88.4	94.8	107.9	36.6	414.3	302.0	72.89
93.4	93.6	103.9	116.2	44.1	453.4	331.0	73.01
103.9	102.1	115.0	130.3	49.8	501.0	368.0	73.45
108.0	108.4	121.2	138.7	51.7	528.0	389.0	73.57
114.2	113.9	128.0	148.1	54.8	558.9	412.0	73.72
121.6	123.9	142.6	164.9	64.0	617.1	456.0	73.89
134.1	125.1	151.2	178.1	71.3	659.7	489.0	74.12

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