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High-power Quasi-continuous Wave Operation of Incoherently Combined Yb-doped Fiber Lasers

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High-energy, high-power, quasi-continuous wave (QCW) operation of double-clad Yb fiber lasers incorporating an incoherent signal combiner is reported. We constructed four efficient, high-power Yb fiber lasers, each of which produced rectangular pulses at 1080 nm with a pulse energy greater than 15 J, and a pulse duration of 10 ms at a repetition rate of 10 Hz, corresponding to an average power of over 150 W and a peak power of over 1.5 kW for ~200 W of incident pump power at 915 nm. These laser outputs were combined by a homemade incoherent fiber signal combiner with low loss, yielding a maximum peak power of ~6.0 kW in a beam with $M^2 \approx 12.5$. The detailed laser characteristics and prospects for further power scaling in QCW operation are discussed.

Keywords : Quasi-continuous wave, Yb fiber laser, High energy, Power scaling, Signal combiner
OCIS codes : (140.3510) Lasers, fiber; (140.3615) Lasers, ytterbium; (140.3410) Laser resonators; (140.3298) Laser beam combining

I. INTRODUCTION

Over the last decade, fiber lasers have shown remarkable progress in performance, leading to the rapid replacement of existing lasers and the development of numerous new applications. The attraction of fiber lasers is not only their capacity to generate high power (output exceeding several kilowatts), but also a number of features that distinguish them from other classes of lasers, such as excellent wall-plug efficiency, robust single-transverse-mode operation, a broad gain bandwidth, and a fully fiberized structure without free-space components [1-8]. However, continuous-wave (CW) operation is not suitable for many applications, due to the need for huge amounts of electrical power, and the great heat generated in the target. On the contrary, pulsed operation by Q-switching or mode locking, which emits laser pulses of high peak power with a pulse width of a few tens of nanoseconds or less, can resolve these issues, but its attainable pulse energy is limited by nonlinear optical scattering, due to the small core area of conventional step-index double-clad fiber. Quasi-continuous wave (QCW) operation is a compromise between these two modes of operation [8, 9]. It produces pulsed output of multikilowatt peak power with a pulse width from a few microseconds to tens of milliseconds, which is long enough to functionally work as CW operation for many applications, but short enough to avoid detrimental thermal effects, while consuming much less electric power than under CW operation. Thus, the QCW operation offers enhanced electrical wall-plug efficiency and better machining quality in applications, and the fiber laser configuration is particularly well suited for this purpose, due to its flexibility in operation and ability to achieve a high average power.

In this paper, we report a high-power QCW fiber laser system comprising four Yb-doped fiber lasers and a home-made incoherent signal combiner. The laser yielded QCW pulses at 1080 nm with ~60 J pulse energy and a 10-ms pulse duration at a 10 Hz repetition rate, corresponding to

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an average power of ~600 W and a peak power of ~6.0 kW for ~889 W of incident pump power at 915 nm.

II. EXPERIMENTS AND RESULTS

The QCW fiber laser system constructed in house was composed of four high-power Yb-doped fiber lasers (YDFL) incorporating a homemade signal combiner. The YDFL configuration used in our experiment is shown in Fig. 1. The Yb double-clad fiber (Nufern, LMA YDF 20/400-VIII) had a Yb-doped core of 20 μm in diameter, surrounded by an octagonal inner cladding of silica 400 μm in diameter. The numerical apertures (NAs) of core and cladding were 0.06 and 0.46 respectively. Pump power was provided by 12 fiber-coupled high-power diode lasers with a 158 W output at 915 nm, via an (18 + 1) × 1 pump/signal combiner. The cladding absorption coefficient for the pump light at 915 nm was ~0.4 dB/m, so a fiber length of ~32 m was used for our experiment. Feedback for lasing was provided by a pair of fiber Bragg gratings (FBGs), one with a high reflectivity (HR) of 99% at 1080 nm and the other with a partial reflectivity of 10% at 1080 nm. The latter FBG served as an output coupler. A single-clad passive fiber ~1 m in length, which had a core 20 μm in diameter and a NA of 0.07 surrounded by a 400-μm-diameter cladding coated with high-index acrylate, was spliced to the output port to remove the residual pump light and the laser signal propagating in the inner cladding. We constructed four YDFLs with the same configuration. The QCW laser operation of the YDFLs was achieved by modulating the applied pump power.

Figure 2 shows the average output powers of the four YDFLs as a function of incident pump powers in the QCW mode of operation, with an applied pulse width of 10 ms at a repetition rate of 10 Hz. The QCW YDFLs yielded 151 W, 155 W, 157 W, and 154 W as maximum average outputs, corresponding to slope efficiencies of 77%, 74%, 65%, and 74% respectively. The slight difference in laser outputs was due to the splicing loss between FBG and Yb fiber. The oscilloscope trace of the QCW output, shown in Fig. 3(a), was measured by a fast silicon photo-

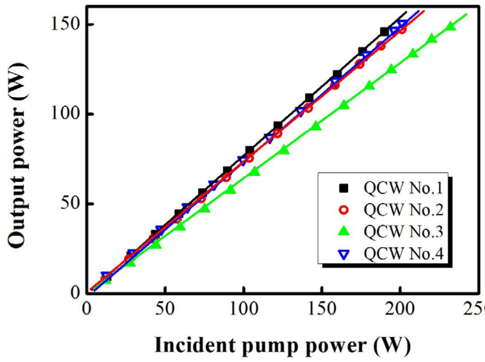


FIG. 2. Average QCW output powers versus incident pump powers for the four Yb fiber lasers at 1080 nm. The laser was operated with a pulse duration of 10 ms at a 10-Hz repetition rate.

detector (Thorlabs PDA400, bandwidth 10 MHz). The output pulses had a pulse duration of 10.12 ms, which was nearly the same as the applied pump pulse width, confirming that the laser signal buildup in the oscillator is fast enough to be negligible. Thus the highest peak powers were calculated to be 1.51 kW, 1.55 kW, 1.57 kW, and 1.54 kW respectively. Figure 3(b) shows that the laser output had a center wavelength of 1080 nm and a 10-dB linewidth of 7.9 nm, as measured by an optical spectrum analyzer (Anritsu MS9710B). Since we used a multimode active fiber, the coiling diameter needed to be carefully managed to optimize the quality of the output beam without degrading laser performance. Assuming that all supported modes are equally excited, the theoretical beam quality M^2 of a multimode beam is given by the weighted average of the participating modes, as follows [4]:

$$M^2 \approx \pi/12 + V/3 \tag{1}$$

The fiber employed was a multimode fiber with V = 4.1, supporting the fundamental LP_{01} mode and three high-order modes, hence its M^2 value was calculated to be 1.63 by Eq. (1). The beam qualities M^2 of the four YDFLs were measured to be less than 1.2 for all power levels, using a scanning-slit beam profiler (Thorlabs BP104-IR). The better

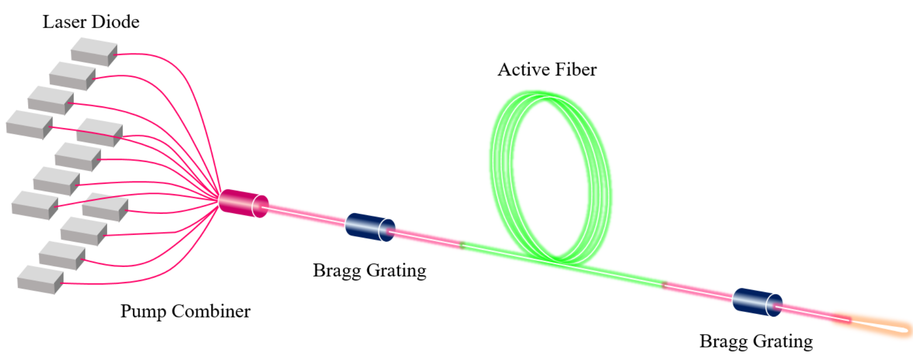
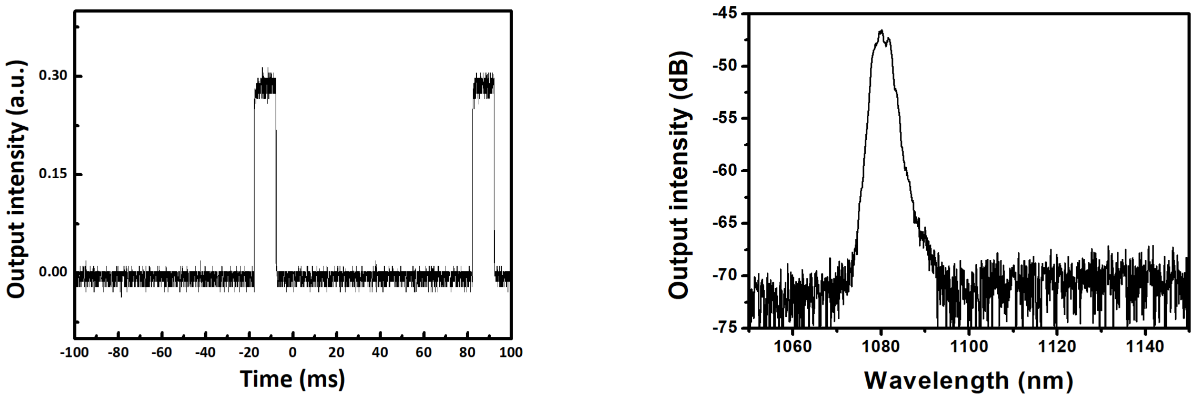


FIG. 1. Schematic of the Yb double-clad fiber laser's configuration.

value of the measured beam quality can be attributed to the higher bending loss of the higher-order modes, due to coiling of the fiber. Much worse beam quality was observed for coiling diameter >15 cm, accompanied by modal instability, but noticeable reduction of laser efficiency was unavoidable for diameter <10 cm, despite the better beam quality. We optimized the coiling diameter of the fiber in the range 10-15 cm.

To combine the laser outputs, we fabricated a 4 × 1 signal combiner, as shown in Fig. 4. It combines the laser beams incoherently, allowing us to achieve high output power in a simple way, without severe degradation of brightness [10-15]. The input single-clad fiber had a 20-μm-diameter core and a 0.07 NA, surrounded by a pure silica cladding 125 μm in diameter. Four input fibers were carefully tapered and spliced to a single-clad output fiber with a 105-μm core and 125-μm cladding, allowing a fiber NA of 0.15. The cross section of the tapered input fiber bundle, and the side view of the splice between the bundle and the output fiber, are shown in Fig. 5. At the splicing



(a) (b)

FIG. 3. (a) Output pulse train and (b) output spectrum of the Yb fiber laser.

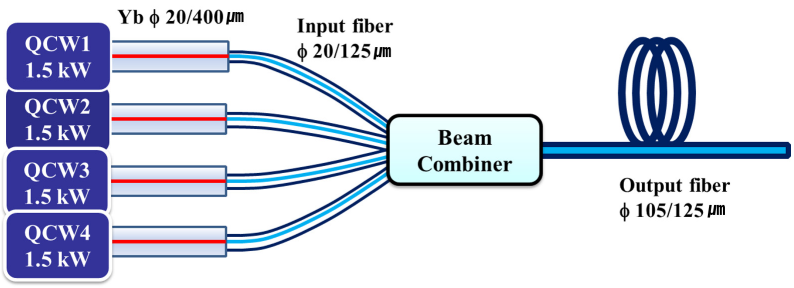
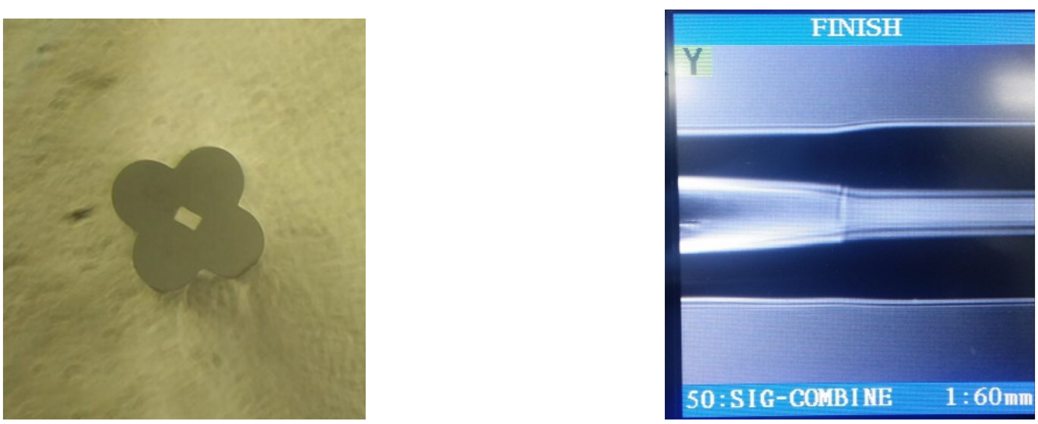


FIG. 4. Schematic of the signal-beam combiner used in this experiment.



(a) (b)

FIG. 5. (a) The cross section of the tapered input fiber bundle, and (b) the side view of the splice between the bundle and the output fiber.

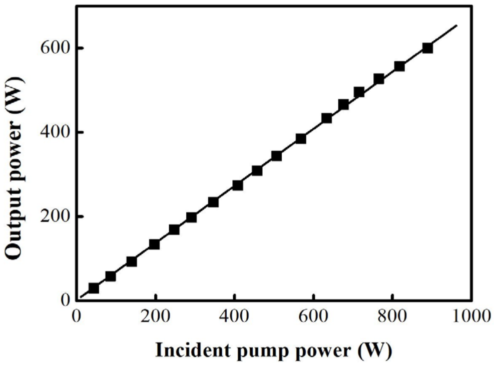


FIG. 6. Average output power as a function of incident pump power, in the QCW mode of the Yb fiber laser system comprising four Yb fiber lasers and the fiber signal combiner.

face, the cores and the combined NA of the input fiber bundle should be covered by those of the output fiber, to minimize coupling loss. Further details of fabrication will be reported in the near future. The transmission efficiency of each port was measured to be 98.1%, 99.3%, 99.8%, and 97.8% respectively. The output end of the YDFL was directly spliced to the input fiber of the signal combiner. Since the core size and NA of two spliced fibers were the same, despite the different cladding sizes, splicing loss could be minimized to less than 0.1 dB via careful adjustment.

Figure 6 shows the combined output power as a function of input pump power. The maximum average output power in QCW mode was 600 W for an incident pump power of 889 W, corresponding to an overall slope efficiency of 68.4%. The total combiner loss was measured to be 0.06 dB. The combined laser pulse had a pulse duration of 10 ms at 10 Hz, and thus a corresponding peak power of 6 kW. The measured beam quality of the output was $M^2 \approx$ 12.5, which was in good agreement with the calculated value of 15.5 from Eq. (1) for an output fiber with V = 45.7.

III. CONCLUSION

In summary, a high-power Yb fiber laser system combining four Yb fiber lasers at 1080 nm was operated in QCW mode, yielding laser pulses of 6 kW in peak power, with a pulse duration of 10 ms at a repetition rate of 10 Hz. Four independent Yb fiber lasers, each with pulsed outputs of greater than 1.5 kW peak power, were incoherently combined by a homemade 4 × 1 signal combiner with very low coupling loss of less than 0.06 dB. The overall slope efficiency of the combined output at 1080 nm was 68.4%, with respect to incident pump power at 915 nm. This QCW fiber laser system incorporating a signal combiner offers the possibility of power scaling along with flexibility in operating conditions, such as repetition rate and pulse width, by controlling the pumping conditions and the temporal synchronization of each laser output. Therefore, further power scaling above tens of kilowatts should be possible via a signal combiner with more input ports, which is the subject of ongoing work.

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