

30W Q-SW fiber laser

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ABSTRACT

We present an adaptive and robust pulse-operated high power fiber laser, which has an average output power of 30 W. The fiber laser realizes flexible pulse duration without changing a repetition rate and an average power, which is desirable for laser processing, by employing a Q-switched (Q-SW) Master Oscillator Power Amplifier(MOPA). For instance, its pulse duration is controllable in the range of 50 ns to 100 ns at 50 kHz in repetition rate. In addition to the flexible pulse duration, the fiber laser provides high powers, a peak power of 27 kW at 30 kHz in repetition rate and an average power of 30 W at 50 kHz in repetition rate. Large mode area (LMA) fibers and end pumping structure in the laser also contribute the above mentioned features, pulse adaptiveness and high output power. In terms of the robustness of the laser, we employ newly-developed reflection-suppressing pump combiners, which protect pump laser diodes (LDs) from amplified reflected signal light from objectives. All those features make the fiber laser a more practical light source for laser processing.

Keywords : Q-switched, fiber laser, pulse, MOPA, peak power, photodarkening, pump combiner

1. INTRODUCTION

Rare-earth doped fiber lasers have become attractive light sources for many laser applications thanks to recent studies. Now many kinds of fiber lasers are commercially available and begin to be used in various applications. Among the applications most of pulsed fiber lasers employ Master Oscillator Power Amplifier (MOPA) configuration since this configuration has potentials which make the laser adaptive. For instance, fiber lasers with the configuration can control their pulse duration and power independently.

In the '90s, fiber lasers suffered from their incompatibility between beam quality and power, since fibers with larger core diameter, which had enabled the fibers to handle more than several tens of watts without nonlinear effects, increased transverse modes in the core and resulted in degradation of beam quality. Many new works have presented to obtain a good beam quality from a fiber with a larger core diameter [1]. Afterward low-NA large mode area (LMA) fibers have broken through this double bind situation [2]. In terms of pulsed operations, LMA fibers have also played important roles to obtain sufficiently stored energy and good beam quality without nonlinear effects and damages [3, 4, 5 and 6]. For example, pulses with 14 kW peak power and ~100 nsec duration from a core diameter of 33 μm was reported in [3], and those with 350 kW and 2.3 nsec from a 30 μm core was reported in [6]. In [4], a practical limit of core diameter of LMA fiber have been suggested to be around 30 μm for more than 10 cm of coiling diameter, so that beam may exhibit a M^2 value less than 2.0. However there are few reports about output pulses of an average power of several tens of watts in a fiber laser with LMA fiber.

Another important requirement for a laser as a light source is its robustness, especially used for material processing. Fiber lasers are robust against mechanical and thermal variation of surroundings since a beam in the laser is guided by the fiber and fiber components fused each other and no alignment error occurs after their assembly. Thus fiber lasers also show advantages over other kinds of laser in terms of robustness. However the only operational threat for fiber lasers is the back reflection light that run back from material outside of the laser into the fiber core since the light may destroy the pump laser diodes (LDs). In particular end pumping structures for amplifying fibers are liable to insufficient isolation from this reflected beam. Therefore it is desirable that a pulsed fiber laser have a "protective wall" against the back reflection.

In this paper, we present Yb-doped silica fiber (YbDF) laser with a MOPA configuration. We first introduce the MO configuration of the fiber laser and the characteristics in the relation ship between pulse duration and power in the laser in section 3. In the same section, we discuss a simple method of controlling a pulse duration and a peak power of the laser. In section 4, we introduce the preamplifier and PA in the fiber laser. In the section we also discuss a component

in the fiber laser and introduce a newly developed beam combiner with reflection suppressed structure, whose function is indispensable to achieve a robust fiber laser. Then we show that the resultant Q-Switched (Q-SW) laser provides a pulse which is of 27 kW in peak power and 30 W in average power, and that the optical characteristic is suitable for material processing. Finally we discuss the reliabilities of the fiber laser in section 5.

2. FIBER LASER DESIGN

Fig.1 shows the schematic diagram of the fiber laser in our study. The architecture of the fiber laser is a 3-stage MOPA configuration, a MO-Preamplifier-PA configuration. Compared to a hi-power oscillator, the master oscillator(MO) is considerably tolerant of components used in the oscillator, and the optical circuitry of the power amplifier(PA) is simpler than that of hi-power oscillator. These features indicate that MOPA configuration can create flexible pulse shape with handling hi-power signal. That is, the architecture can successfully balance flexibility and scalability. A signal wavelength is arbitrarily chosen by means of a band pass filter (BPF) located in MO. In this article, we propose two different signal wavelengths, (1040 nm and 1065 nm). The full width of half maximum (FWHM) of the BPFs are 2 nm for 1065 nm and 50 nm for 1040 nm. For obtaining a narrower pulse duration, the signal wavelength should be around 1040 nm. This is because the single-pass gain of the Yb fiber takes the maximum value at the wavelength, and oscillator generates the pulse with the shortest duration. For the higher pulse energy, a signal wavelength should be longer than 1060 nm. This is because a small-signal gain in the PA stays lower at these wavelengths and the PA can store an energy without spurious lasing. We insert the preamplifier after the MO to boost up the signal before it goes into the PA.

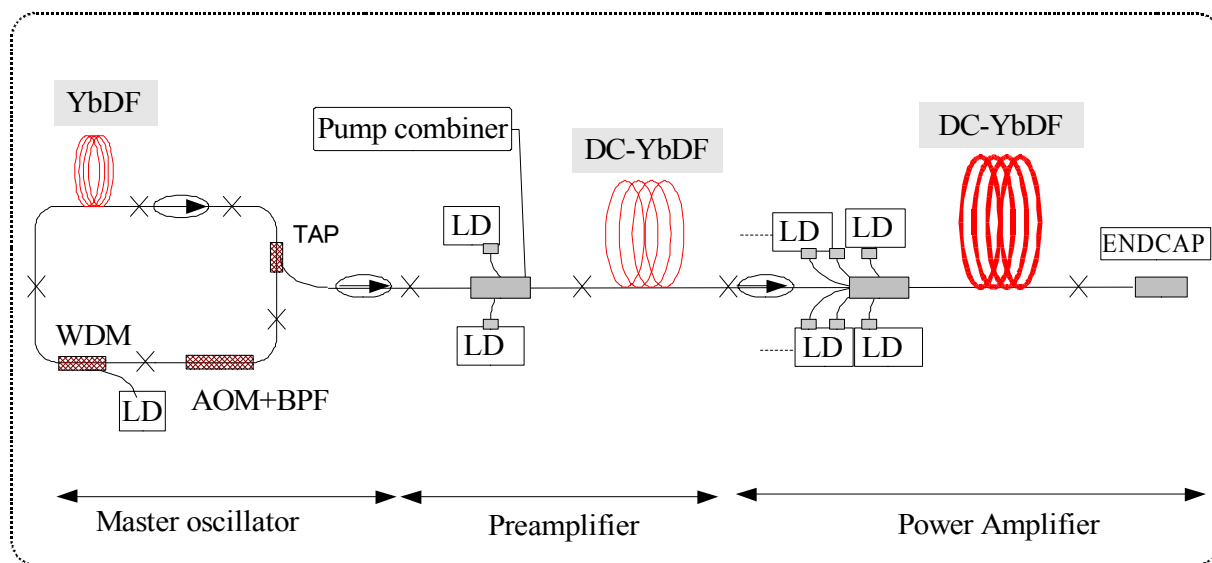


Fig. 1 Schematic diagram of MO-Preamplifier-PA fiber laser

3. Q-SW FIBER RING LASER

We adopt a ring configuration in the MO (Fig. 1). Feedback of amplified spontaneous emission (ASE) for gain fiber is relatively lower in a ring laser, and as a result, the gain fiber can store higher energy. In other words, we can easily have lower value of Q-factor in the ring laser at the same population inversion. For this reason, a ring configuration is suitable for pulse operation and we adopt the configuration in our fiber laser.

The MO in the laser consists of simple circuitry which has single-mode waveguide, single pump LD and conventional components in optical communication. We employed an YbDF which has 3/125 core/clad dimension and a pump LD which has the center wavelength of 976 nm. The pump LD has a single-mode pigtail fiber and the LD is operated with power-control and temperature-control modes. The YbDF is continuously pumped and, repetitively Q-switched in the operating regime of the ring laser. An acousto-optic modulator(AOM) is used as a Q-switching device. The total length of the ring is 3.5m for all conditions. Fig. 2 shows examples of spectral characteristics and temporal shapes of output pulse of the MO. From the spectrum plot, we confirmed the lasing wavelength is corresponding to the center wavelength of BPF. And in each repetition rate, pulses show smooth shape with single peak. The results indicate that the length of the cavity is optimized.

Fig. 3 shows the pulse duration and the peak power as a function of repetition rate for different pump powers, at a signal wavelength of 1040 nm(fig. 3a) and that of 1065 nm(fig. 3b). At both wavelengths, the pulse duration increases while peak power decreases in the range of all repetition rate.

The pulses generated from the same cavity at different wavelength show clear contrast in pulse duration and peak power. The pulse durations of 1040 nm are globally shorter than those of 1065 nm and the peak powers are higher at 1040 nm than at 1065 nm. The discrepancy is due to the spectrum of small-signal gain for the YbDF. Basically pulse duration depends on the cavity length and small-signal gain in the cavity. And a shorter pulse duration is generated from a cavity with a higher small-signal gain. The small-signal gain at 1040 nm is considerably higher than that at 1065 nm, so that the pulse durations are shorter and the peak powers are higher in 1040nm. These results indicate that the wavelength of signal can be chosen according to the purpose or the application of the fiber laser.

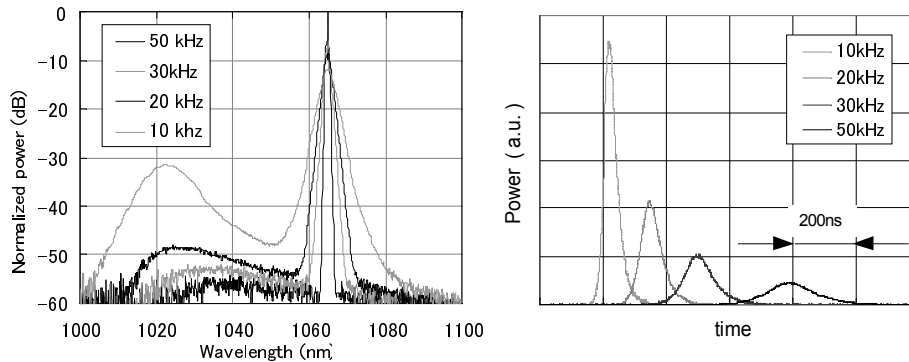


Fig. 2 Example of spectrum and pulse shape (signal at 1065nm, pump = 320mW)

The figures also suggest that the pump power has significant influences on the pulse shape. The left plot of fig. 3a indicates that at 50 kHz, the pulse duration is 55 nsec (Pump = 400 mW) or 110 nsec (Pump = 180 mW) for 1040 nm. The left plot of fig. 3b indicates that the pulse duration is 130 nsec (Pump = 400 mW) or 300 nsec (Pump = 180mW) for 1065 nm. These discrepancies are also due to the spectrum of small-signal gain for the YbDF. The obtained results suggest that the pulse duration at each repetition rate can be controlled by controlling the output power of pump LD. This pump-power dependence of pulse duration seems to have difficulty with adaptive operation which requires independent controllability from pulse duration and output power. For instance the average output powers vary from 90 mW to 45 mW when pump powers change from 400 mW to 180mW. However we can exploit this dependence to control pulse duration at the same repetition rate without deteriorating its adaptiveness. The pulse duration can be controlled by controlling the pump power without affecting the output power of the laser, since the variation of MO

output power can easily be compensated in the preamplifier or otherwise PA. Thus the results obtained show that pulse duration, which is one of the most important factors in pulsed laser, can be controlled in a simple method. In summary, the MO with ring configuration have advantages in generating pulses with flexible pulse durations. Further more, the variation range of pulse durations can be altered by adjusting the signal wavelength.

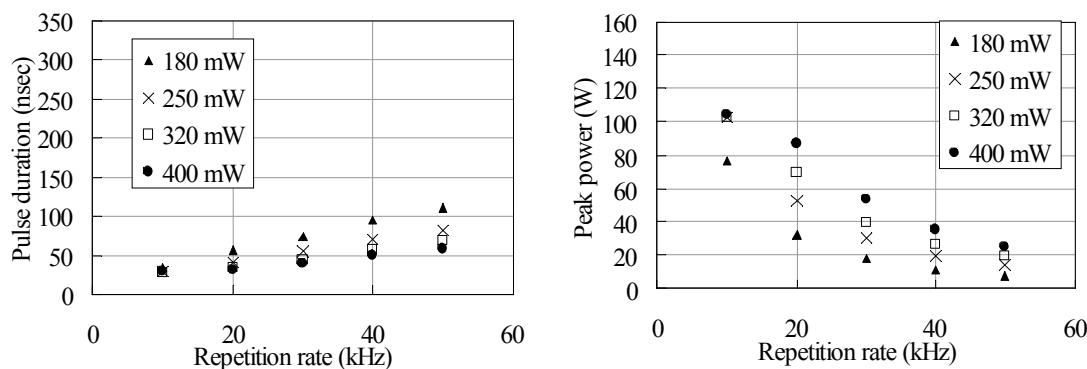


Fig. 3a : Pulse duration and peak power versus repetition rate (signal at 1040 nm)

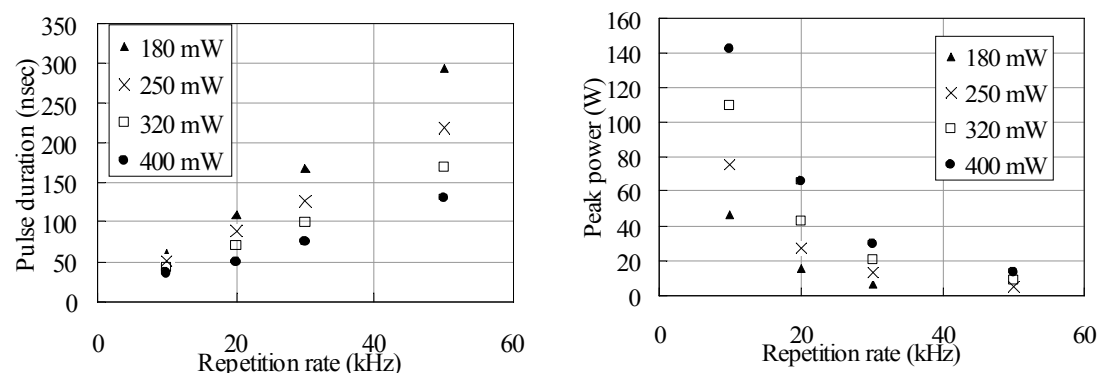


Fig. 3b : Pulse duration and peak power versus repetition rate (signal at 1065 nm)

Fig. 3 : Comparison of pulse shape at different signal wavelength and pumping power

4. CLADDING PUMPED FIBER AMPLIFIER

Both the preamplifier and the power amplifier (PA) are composed of single-emitter LDs, a multi-port pump combiner and a double clad (DC) YbDF. In the PA, the pump light from LDs is delivered into the inner cladding of the DC-YbDF with end pumping method. The preamplifier has the same configuration as the PA but pumping at ~ 3 W whereas the PA is pumped at ~ 70 W (915 nm). The pump power in the preamplifier is controlled so that the preamp. emits 800 mW in an average power. The DC-YbDF in the PA is of a 30/400 μm core/cladding diameter. The output end of the DC-YbDF is spliced to a LMA fiber whose another end is spliced to a silica rod as an end cap. The end cap has no anti-reflection coating or angle-polished face to simulate an actual operating condition, under which lasers are exposed to reflected light from its target material. The reflection from the end cap is adjusted to ~ -30 dB by controlling its length as ~ 2 mm. The preamplifier and the PA have a simple configuration with a LMA-YbDF and a pump combiner for end pumping. We employ a newly-developed unique pump combiner in our fiber laser. The schematic diagram of the pump combiner is shown in Fig. 4. As shown in the figure, each multi-mode fiber from a single emitted LD is put into a silica capillary, which has multiple through holes inside like a lotus root, and the fibers and capillary are fused by heat. Then the unified capillary is spliced to a bridging triple clad fiber. The most important part in the beam combiner is the tapered bridging fiber. The fiber enables the ideal coupling of signal light at the interface to DC-YbDF while it enables the ideal coupling

of pump light to the inner cladding of DC-YbDF at the same time. The MFDs of signal light in the MO and PA are so different at the interface between the MO and PA that some kinds of a MFD converter is needed there. In the beam combiner, tapered bridging fiber has a function of the MFD converter. When the bridging fiber reduces its core size along with the taper down to the interface, the optical confinement of core becomes weak and the MFD of signal light increases upto the similar size of that of LMA-YbDF. Utilizing this function we have obtained the combiner with a loss of 0.18 dB and 0.6 dB in average for pump port and signal port, respectively. Thanks to the pump combiner, the power of input signal and pump lights are estimated to be 700 mW(= 800 mW x 87 %) and 67 W(= 70 W x 96 %), respectively. Practically, the estimated power of each light is sufficient for our target power, 30 W in average. Thus in terms of the coupling loss, the pump combiner is suitable for the PA which handles several tens of watt.

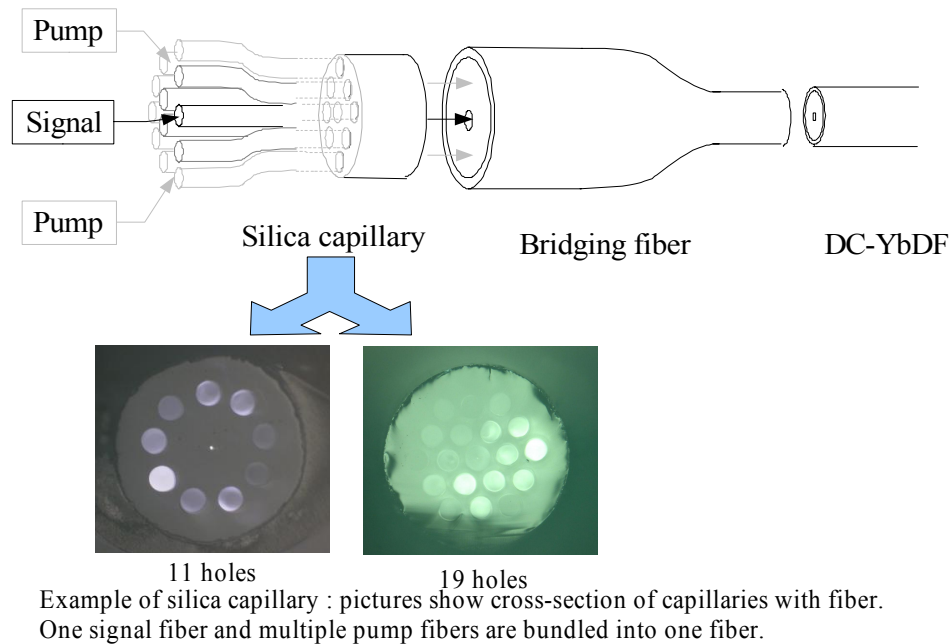


Fig. 4 Schematic view of pump combiner with multiple-hole capillary

Figure 5 shows output power of the fiber laser as a function of pump power. The maximum average power of the laser exceeds 30 W at 66 W pump power, and the slope efficiency and threshold are 54 % and 10 W respectively, at 1040 nm in signal wavelength and 50kHz in repetition rate. At 30 kHz in repetition rate, the average power and the peak power reach 27 W and 27 kW for pulse duration = 33 nsec. In the range of an average power above 27W, the PA becomes unstable due to the ASE reflection from the end cap. Prime results we obtained are shown in table 1 for the signal wavelength of 1040 nm and 1065 nm. These results above for both wavelengths indicate that the fiber laser is suitable for material processing and especially for surface treatment.

We have introduced the unique pump combiner that realizes the ideal splicing. The pump combiner can also protect pump LDs from reflected signal light. A laser is occasionally exposed to reflection from targeted material. And to make matters worse, pump LDs are not perfectly isolated from reflected signal and spurious lasing in end pumping structure. In particular, the mismatching of propagation mode in DC-YbDF and bridging fiber causes leak light at the splicing point, and this leak light can go into pump ports and destroy LDs. So we put an inner cladding just around the core of bridging fiber to confine the leaked signal light in it. The inner cladding (we call it “protection wall”) is a sort of waveguide for the leaked signal light and this waveguide continuously connected to the cladding of the signal port of combiner (see schematic view in Table 2). Incorporating the protection wall in our pump combiner, the isolation of pump port from reflected signal light is improved (see table 2). The result indicates that even if reflected signal exceeds 10 kW in peak power, only less than 4 W peak power can reach the pump LD whose typical output power is more than 5

W (continuous wave). To confirm the estimation, we did free running test, where 70 W in pump light was provided into the DC-YbDF without any signal. In the test, we observed giant pulses which could easily destroy pump LDs. We repeated this test a few times and found no failure in the pump LDs . From all the results above, we should conclude that any reflection from the outside of the laser or any spurious lasing could not affect the life of pump LDs.

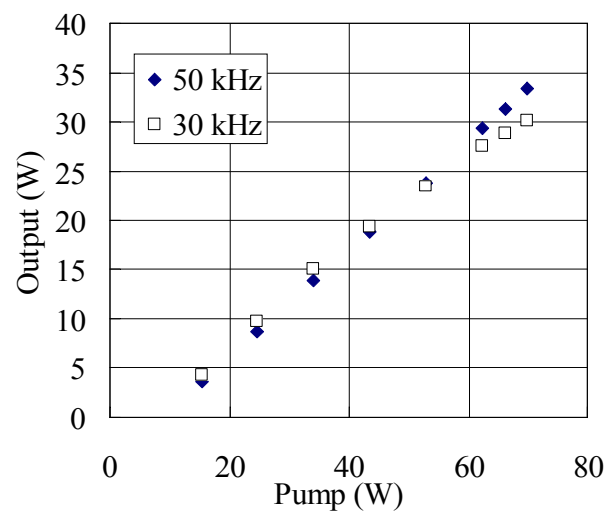


Fig. 5 Laser output as a function of pump power which is measured directly from pump LDs
 signal wavelength = 1040 nm
 slope = 54 %, threshold = 10 W

Table 1 Measured results of 3-stage MO-PA fiber laser for 2 signal wavelengths at different repetition rates

	1040 nm		1065 nm	
repetition rate	50 kHz	30 kHz	50 kHz	20 kHz
pulse duration	50 nsec	33 nsec	120 nsec	45 nsec
average power	> 30 W	27 W	> 30 W	20 W
peak power	> 12 kW	27 kW	> 5 kW	22 kW

The LMA fiber employed in PA keeps quasi single-mode operation. The coiling diameter is 120 mm and core/cladding NA is 0.07. As discussed in references [1,3 and 4], it is difficult to filter higher-order modes by coiling the fiber with the diameter. If one of the higher-order modes is excited at the input end of LMA-YbDF by input signal light, the beam quality of output light of the fiber laser degrades considerably [5]. Thus exciting the fundamental mode at the interface between the pump combiner and the LMA-YbDF is critically important for the beam quality. In order for the signal light not to couple to a higher-order mode, we evaluated the splice loss at the interface only by the fundamental mode.

We confirmed the coupling efficiency is over 85 % for all cases. The images of the beam spot emitted from the beam combiner is shown in fig. 6a and that from the laser in fig. 6b. M^2 for fig. 6a is 1.2 and that for fig. 6b is 1.5. We can find a little degradation of beam quality in the DC-YbDF in the PA from the results and further investigation is underway now. However the beam quality is sufficient for material processing and the results indicate the importance of the coupling at the interface between the combiner and the DC-YbDF. In this section, we have introduced configuration of the PA and the structure of the pump combiner, and then we have showed the optical characteristic and robustness of the laser. All the results support that the proposed fiber laser is practical light source for material processing.

Table 2 Comparison of the isolations for traditional combiner and proposed combiner

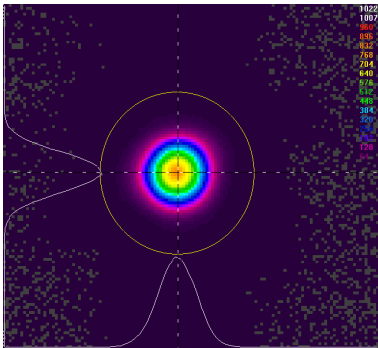
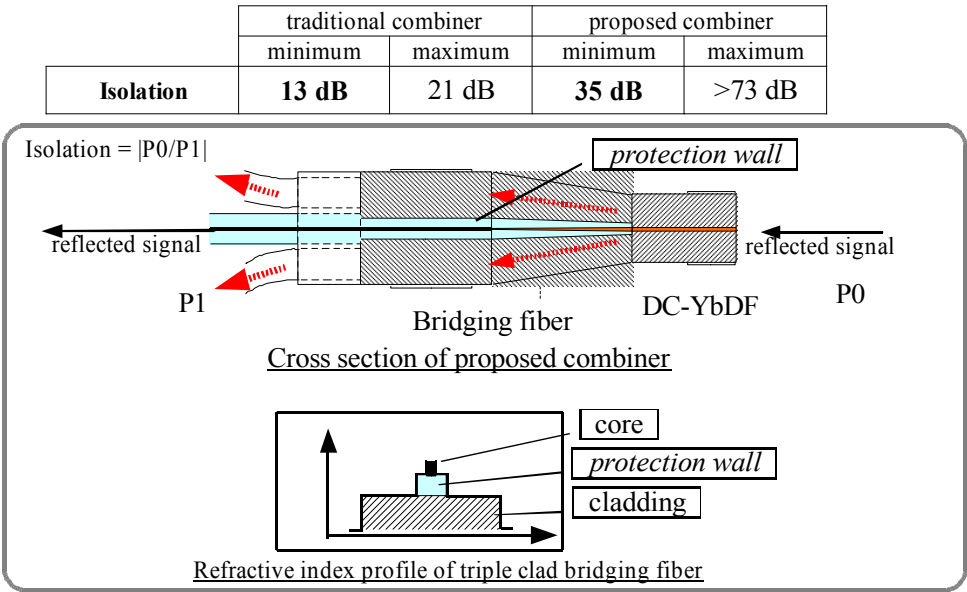


Fig. 6a measured beam image of combiner output

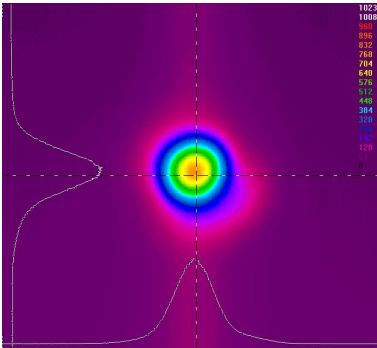


Fig. 6b measured beam image of laser output

Fig. 6 Comparison of beam images (input and output of PA)

5. RELIABILITY

In terms of long term reliability of a fiber laser, the probability of failure of pump LDs is a critical matter. However their dominant failure mode is a random failure and we employ multiple single-emitter LDs in the fiber laser. So redundancy in pump LD can increase the life time of the fiber laser. In the sense of fatality a failure in a pump combiner and YbDF is more critical than that in LD. Because once they occurs, they must cause fatal effect for the life of the laser. Recently the degradation in YbDF has been reported which is called “photodarkening” [7 and 8]. The photodarkening induces a permanent excess loss in Yb-doped region of fiber, and it is driven by pump light. Basically YbDF with higher Yb concentration takes the degradation, but it is possible to reduce the effect. We have studied the photodarkening in Yb-DFs [7]. In this work, we employ the YbDF with less photodarkening effect in the fiber laser.

To confirm the total reliability of the fiber laser, we measure the output power for 5000 hr under pulse operation. The results are shown in Fig. 7. Our estimation before the test indicated that output power reduction after 5000hr should be 5-6% due to photodarkening. The overall decay of its output power is less than 5 % after the test. From the result it is found that the decay in output power is mainly caused by degradation in YbDF. The decay should be easily compensated by controlling pump power and therefore it is acceptable for most of applications.

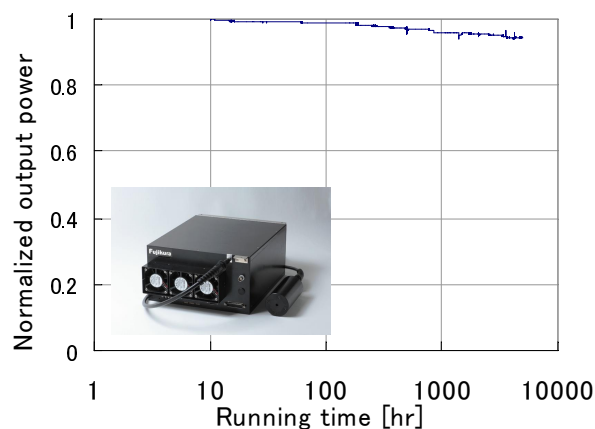


Fig. 7 Normalized output power as a function of logarithm of time

6. SUMMARY

In this paper, we have introduced Q-SW fiber laser with MOPA configuration. The features of this fiber laser is

1. flexible pulse durations form MOPA configuration,
2. 27 kW in peak power from a LMA-YbDF with a 30 μm core,
3. Robustness against the reflection from a newly designed pump combiner.

All these features make the fiber laser suitable for material processing. Discussions in this article have clarified not only the advantage of a MOPA configuration and LMA fiber but also importance of improvement on an optical component for end pumping structure. A newly-developed reflection-suppressed pump combiner has been reported and improves the total reliability of fiber laser. This work has expanded the possibility for applying fiber laser to material processing and future work for improvement will promise the robustness to a practical level.

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