3 kW single stage all-fiber Yb-doped single-mode fiber laser for highly reflective and highly thermal conductive materials processing

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ABSTRACT

A 3 kW single stage all-fiber Yb-doped single-mode fiber laser with bi-directional pumping configuration has been demonstrated. Our newly developed high-power LD modules are employed for a high available pump power of 4.9 kW. The length of the delivery fiber is 20 m which is long enough to be used in most of laser processing machines. An output power of 3 kW was achieved at a pump power of 4.23 kW. The slope efficiency was 70%. SRS was able to be suppressed at the same output power by increasing ratio of backward pump power. The SRS level was improved by 5dB when 57% backward pump ratio was adopted compared with the case of 50%. SRS was 35dB below the laser power at the output power of 3 kW even with a 20-m delivery fiber. The M-squared factor was 1.3. Single-mode beam quality was obtained. To evaluate practical utility of the 3 kW single-mode fiber laser, a Bead-on-Plate (BoP) test onto a pure copper plate was executed. The BoP test onto a copper plate was made without stopping or damaging the laser system. That indicates our high power single-mode fiber lasers can be used practically in processing of materials with high reflectivity and high thermal conductivity.

1. INTRODUCTION

Power growth of Yb-doped fiber lasers leads to new laser material processing applications. In automotive and renewable energy fields, high power lasers are attractive tools for welding of highly electrical conductive materials such as Cu and Al. A single-mode Yb-doped fiber laser with excellent beam quality and several kW output power is believed to realize both a large working area and high intensity for laser welding of highly reflective and thermal conductive materials mentioned above. Recently, several high power single-mode Yb-doped fiber lasers with a MOPA (master oscillator power amplifier) configuration were reported [1][2]. However, a MOPA system is vulnerable to reflection from materials during processing especially at the beginning because of output power instability. And a MOPA system needs more components compared with a single-stage Fabry-Perot system. Moreover transverse mode instability has to be considered when MOPA configuration is adopted. In our previous work, a 2 kW single-mode fiber laser with single-stage Fabry-Perot system and long delivery fiber was reported [3]. Stimulated Raman Scattering (SRS) which causes laser output fluctuation was strongly suppressed during laser processing of highly reflective materials. In materials processing, SRS threshold becomes lower due to coupling of the reflected Stokes light from the processed materials back into the single-mode fiber laser. For the above-mentioned applications, more output power of a single-mode fiber laser is expected. In this work, a 3 kW single stage all-fiber single-mode fiber laser with 20-m long delivery fiber was demonstrated. And to evaluate practical utility of the 3 kW single-mode fiber laser, processing tests onto materials with high reflectivity and high thermal conductivity was executed.

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2. FIBER LASER CONFIGURATION

Figure 1 shows the schematic configuration of the 3 kW all-fiber Yb-doped single-mode fiber laser with single-stage Fabry-Perot system. From the standpoint of environmental stability, a fiber laser desirably consists only of fiber components. All devices, such as pump LDs, FBGs and the Yb-doped fiber, of the fiber laser were fabricated in-house. A bi-directional pumping scheme was adopted in order to launch high pump power and avoid local excess heat. The maximum launchable pump power increased up to 4.9 kW by using our newly developed high-power LD modules [4]. The length of the delivery fiber was 20 m which is long enough to be used in most of laser processing machines. The effective core area A_{eff} of fibers used in the 3 kW single-mode fiber laser were 400 μm^2 which is the same value as fibers used in the 2 kW single-mode fiber laser, because Raman threshold power which is defined as the incident power when the output Stokes light becomes equal to the remaining power of the incident light was designed to be 3.5 kW for the previously reported 2 kW fiber laser.

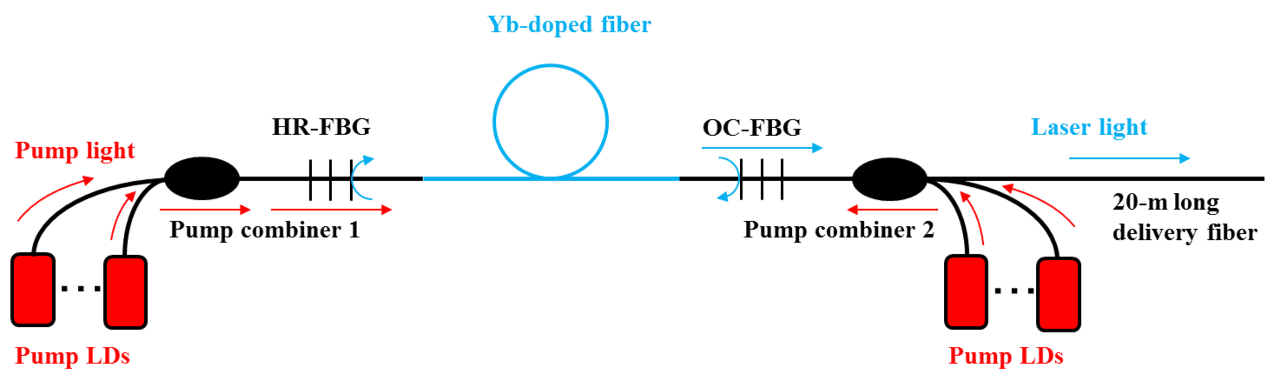

Figure 1. Schematic configuration of 3 kW single-mode fiber laser.

3. PROCESSING TEST CONDITIONS

To evaluate practical utility of the 3 kW single-mode fiber laser, processing test onto a highly reflective and highly thermal conductive materials was executed. Table 1 shows test conditions of the processing.

Table 1. Test conditions of the processing.

Optical magnification of the processing head	1
Tilt of the processing head	9 degrees
Material	Pure cooper plate (C1040)
Focusing point	Surface of the pure copper plate Bead on Plate (BoP)
Processing speed	6 meter per min.

During the processing test, monitors installed in the laser system were checked to evaluate the SRS suppression technique.

4. ESTIMATION OF RAMAN GAIN

The gain of Stokes light in the fiber laser is expressed as

$$G[dB] = \frac{10}{\ln 10} \cdot \frac{P g_R L_{eff}}{A_{eff}} \quad (1)$$

where G is the gain of Stokes light, P is the laser output power, A_{eff} is the effective core area of the fiber, g_R is the Raman-gain coefficient, and L_{eff} is the effective fiber length, respectively. Here, we use the value of $g_R \approx 5\times10^{-14}$ W/m assuming that the polarization between pump wave is completely scrambled. In the 3 kW single-mode fiber laser, P, A_{eff}, and L_{eff}, are 3 kW, 400 μm^2, and 50 m respectively. The gain of Stokes light is estimated at 50dB.

On another test result, the fiber recoupling efficiency under the test condition detailed in Table 1 was about 0.001%.

During the processing test, the Stokes light which is reflected from the copper plate and recoupled to the delivery fiber is estimated to be amplified to the same level of the Stokes light power contained in the single-mode fiber laser at near HR-FBG. For the reasons stated above, the 3 kW single-mode fiber laser is expected to run processing test without stopping or being damaged.

5. OPTICAL CHARACTERISTICS OF FIBER LASER

5.1 Output characteristics

Figure 2 shows the laser output power as a function of pump power. The output power reached 3 kW at a pump power of 4.23 kW. The slope efficiency was 70%. The beam profile at the focal point is also shown in Figure 2. The M-squared factor was 1.3. Single-mode beam quality was obtained.

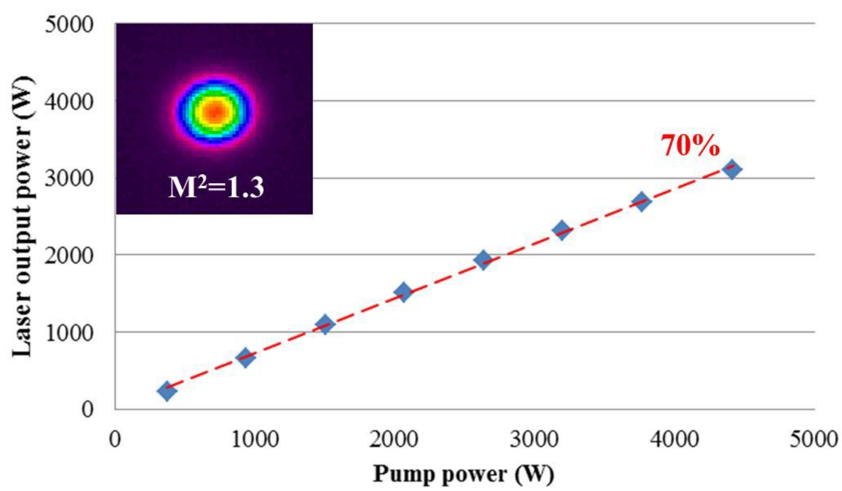

Figure 2. Laser output power as a function of pump power and beam profile at the focal point.

5.2 Output power spectrums

SRS was able to be suppressed at the same output power by increasing ratio of backward pump power. Figure 3 shows the measured output spectra at the laser output power of 3 kW for different ratios of backward pump power. The SRS level was improved by 5dB when 57% pump ratios was adopted compared with the case of 50%. As a consequence, SRS was 35dB below the laser power at the output power of 3 kW even with a 20-m delivery fiber, which indicates that output fluctuation would be strongly suppressed in laser processing of highly reflective materials.

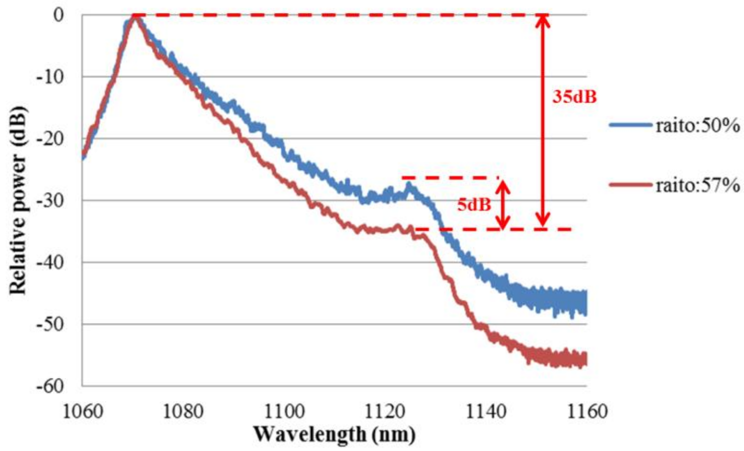

Figure 3. Output spectra at the laser output power of 3 kW with different ratios of backward pump power.

6. PROCESSING TEST RESULTS

The processing tests described in chapter 3 were executed. Figure 4 shows the surface and the cross-section of the bead. The bead width and the penetration depth of the molten copper were 600 μm and 2.6 mm, respectively. Figure 5 shows the cross-section of the copper plate which was molten by 3 kW multi-mode fiber laser for the sake of comparison. The bead width of the copper plate molten by the single-mode fiber laser was 0.4 times narrower than that of the copper plate molten by the multi-mode fiber laser. And moreover the penetration depth of the copper plate molten by the single-mode fiber laser was 4.1 times deeper than that of the copper plate molten by the multi-mode fiber laser. Our SRS suppression technique worked very successfully since the laser system was able to run without stopping or being damaged.

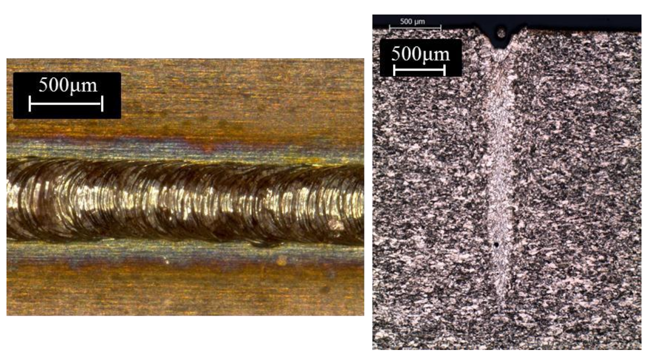

Figure 4. Surface and cross-section of the copper plate molten by the 3 kW single-mode fiber laser .

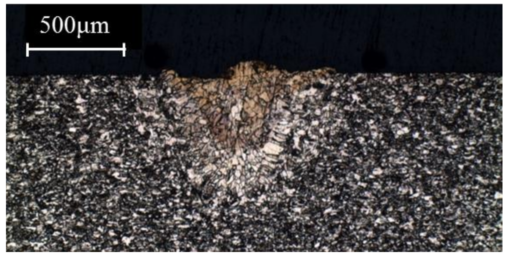

Figure 5. Cross-section of the copper plate which was molten by the 3 kW multi-mode fiber laser.

Figure 6 shows the penetration depth and the bead width of the molten copper as a function of output power. The penetration depth was linear to the output power. On the other hand, the bead width was nearly constant with the output power. Those correlations represent characteristic of a single-mode fiber laser which is nearly diffraction-limited beam quality.

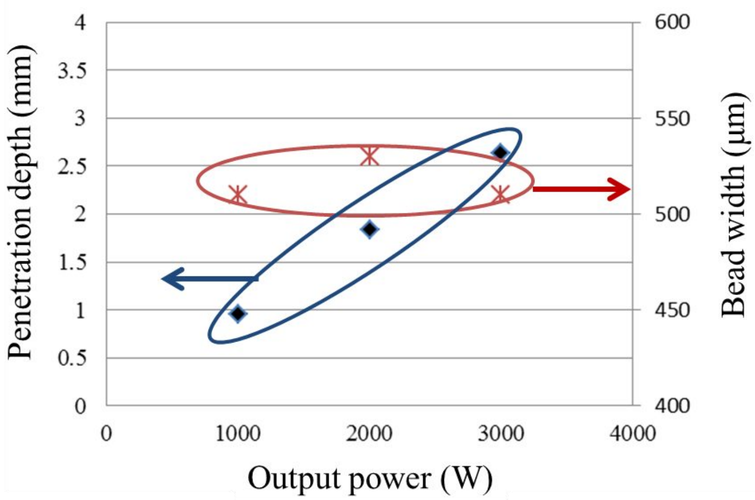

Figure 6. Penetration depth and bead width of the molten copper as a function of output power.

7. DISCUSSION

To realize higher power all-fiber Yb-doped single-mode fiber laser with practical utility, G which is the gain of Stokes light in the fiber laser should be at the same level as that of the 3 kW single-mode fiber laser. From equation (1), an increase of P is associated with an increase of A_{eff} or a decrease of L_{eff} or both. Figure 7 shows relations between the effective core area of the fiber and the effective fiber length at each the laser output power under the condition that the gain of Stokes light is fixed 50dB. Increasing of A_{eff} may cause deterioration of the beam quality due to the increase of transverse modes. Decreasing of L_{eff} may result in shortening of the delivery fiber. Therefore A_{eff} and L_{eff} should be designed carefully within the trade-off between the beam quality and the delivery fiber length for a higher output power.

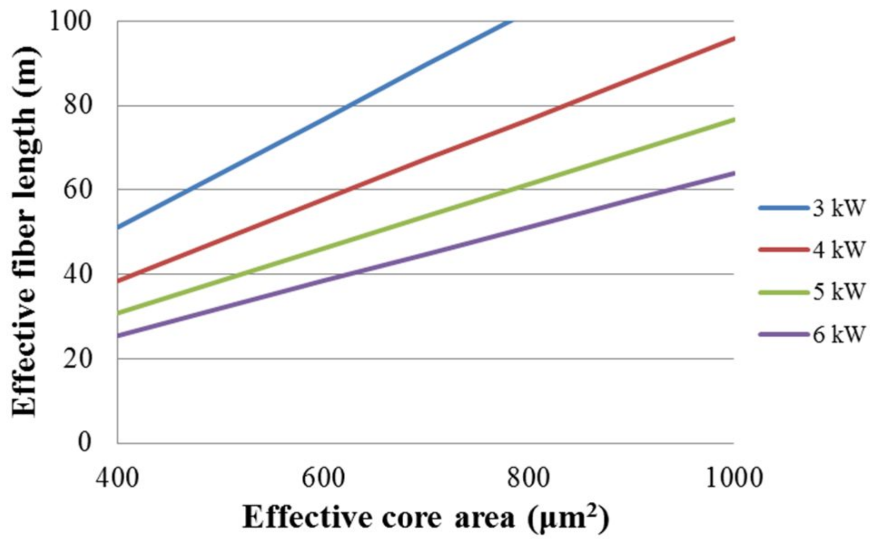

Figure 7. Relations between the effective core area of the fiber and the effective fiber length under the condition that the gain of Stokes light is fixed 50dB.

8. SUMMARY

A 3 kW single stage all-fiber single-mode fiber laser with 20-m long delivery fiber has been demonstrated. BoP test onto a copper plate was made without stopping or damaging the laser system, which indicates our high power single-mode fiber lasers can be used practically in processing of materials with high reflectivity and high thermal conductivity.

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