2 kW single-mode fiber laser with 20-m long delivery fiber and high SRS suppression

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ABSTRACT

A 2 kw single-mode fiber laser with a 20-m long delivery fiber and high back reflection resistance has been demonstrated. An Yb-doped fiber with large core size and differential modal gain is used to realize high SRS suppression and single-mode operation simultaneously. The 20 m-long delivery fiber gives flexibility to the design of processing systems. An output power of 2 kW is achieved at a pump power of 2.86 kW. The slope efficiency is 70%. The power of the Stokes light is less than -50 dB below the laser power at the output power of 2 kW even with a 20-m delivery fiber. Nearly diffraction-limited beam quality is also confirmed ($M^2 = 1.2$). An output power of 3 kW is believed to be achieved by increasing pumping power. The back reflection resistance properties of the fabricated single-mode fiber laser is evaluated numerically by the SRS gain calculated from measured laser output spectra and fiber characteristics. The acceptable power of the back reflection light into the fiber core is estimated to be 500 W which is high enough for processing of highly reflective materials. The output power fluctuation caused by SRS and back reflection in materials processing will be well suppressed. Our high power single-mode fiber lasers can provide high quality and stable processing of highly reflective materials.

Keywords: Fiber lasers, Stimulated Raman Scattering, differential modal gain

1. INTRODUCTION

A high power single-mode fiber laser is an attractive laser source which has various application fields such as materials processing and long-distance laser energy transmission [1], and so on. A fiber laser is able to provide an excellent beam quality. Especially a fiber laser with single mode core fibers that have a small core or a low core-clad refractive index difference can produce a diffraction limit beam automatically. However, the effective mode area of fiber due to the small core likely causes Stimulated Raman Scattering (SRS). Because the power density in the fiber becomes high. When SRS is excessively generated in the fiber laser, the majority of the laser light power is transferred to the Stokes light. It results in the output power instability of the fiber laser. Backward SRS is also damagingly raised by the reflected light from the optics or the workpiece in a practical laser system. Therefore, a laser with high SRS suppression is desired for stable operation of a laser system.

A 2 kW single mode fiber laser has been reported by A. Rosales-Garcia et al. whose configuration is a master oscillator power amplifier (MOPA) [2]. The core diameter of the master oscillator (MO) and the Power Amplifier (PA) are 11µm and 14 µm, respectively, and the total fiber length under single-mode operation is estimated to be around 40 m. The ratio of the laser light power to the Stokes light power at the output power of 2.1 kW is -30 dB. Due to its small effective core area of the fibers in the fiber laser, significant laser output power fluctuation would be anticipated when increasing the output light power or using a long delivery fiber. If we use a short delivery fiber in order to suppress SRS, the distance between the laser oscillator and the beam output end of the laser irradiation system will be also short consequently. That limits the flexibility of the design of laser irradiation systems.

In this paper, we report a single-mode fiber laser with a 20-m long delivery fiber and high SRS suppression that allows design flexibility of the laser systems.

2. DESIGN OF FIBER PARAMETERS

2.1 FIBER PARAMETERS

The number of transverse modes of the fiber is related to the v parameter. If we assume a step index fiber, we can write the v parameter as

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$$v = \frac{2\pi a}{\lambda_0} NA \tag{1}$$

where λ_0 is the wavelength of light which propagates in the fiber core, α is the core radius, and NA is the numerical aperture of the core which is expressed as

$$NA \equiv \sqrt{n_{core}^2 - n_{clad}^2} \tag{2}$$

where n_{core} is the refractive index of the core and n_{clad} is the index of the cladding. In a fiber laser, the NA is desired to be greater than 0.07 in order to avoid bending loss and instable core index on fiber fabrication. On the other hand, deterioration of the beam quality by mode coupling is anticipated when the fiber has many transverse modes due to a high NA. The v parameter is desirable to be less than 6 in order to avoid the beam quality deterioration. Figure 1 shows the relationship between NA and effective area of the fundamental mode of the fiber in case of v = 6 and λ_0 = 1080 nm. According to Figure 1, the effective area must be less than 450 μm^2 at the NA of 0.07. Then we set a target effective core area of 400 μm^2.

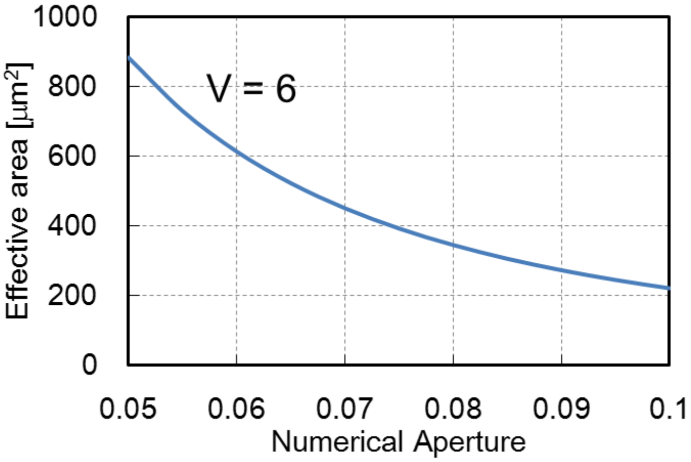

Figure 1. The relation between effective area and Numerical Aperture of the fiber at v = 6.

2.2 Raman threshold power

The Raman threshold power P_{th} of the SRS in a fiber is defined as an incident power when the output Stokes light becomes equal to the remaining power of the incident light. It is represented by the following equation [3]:

$$P_{th} \approx \frac{16A_{eff}}{g_R L} \tag{3}$$

where A_{eff} is the effective core area of the fiber, g_{R} is the Raman-gain coefficient, and L is the fiber length, respectively. Firstly, to determine the fiber parameters roughly, we used equation (3).

Figure 2 shows the calculated values of the effective core area to achieve Raman threshold powers as a function of the fiber length. Here, we used the value of $g_{\mathrm{R}} \approx 5\times10^{-14}$ W/m assuming that the polarization between pump wave is completely scrambled. From the calculation results, we can roughly predict that the acceptable fiber length is 60 m when we adopt the effective area of 400 μm^2 in case of the threshold power of 2000W. This allows the fiber length of the laser oscillator of 40 m even if the delivery fiber is 20 m. The fiber laser oscillator length of 40 m is long enough to absorb the pump light sufficiently.

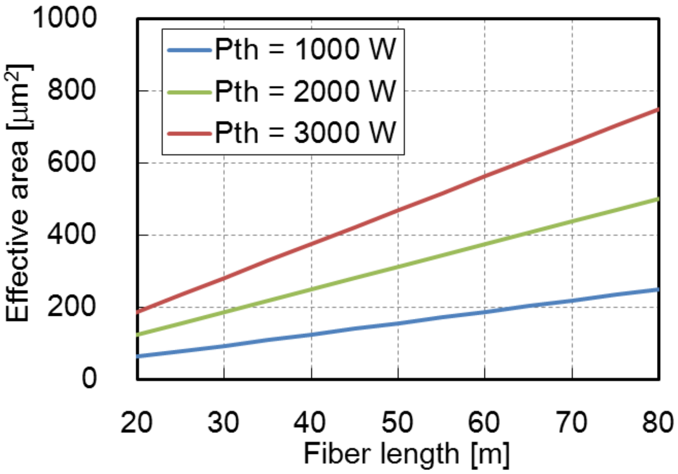

Figure 2. Calculated value of the effective area of the fundamental mode versus fiber length for the Raman threshold powers of 1, 2, and 3 kW.

3. DESIGN OF FIBER LASER

Figure 3 shows the schematic configuration of the fabricated 2 kW single-mode fiber laser with a 20-m long delivery fiber. All devices, such as pump LDs, FBGs and the Yb-doped fiber were fabricated in-house. A bi-directional pumping scheme is adopted to introduce a high pump power and to avoid excess heat at pump combiners. The pump LDs used in the laser are 915-nm-high-power single emitters. Due to their Asymmetric Decoupled Confinement Heterostructure (ADCH), they show high reliability [4]. The maximum launchable pump power was totally 3 kW. The laser cavity consists of a HR-FBG, an OC-FBG and an Yb-doped fiber. The reflectances of the HR-FBG and the OC-FBG at 1080 nm were more than 99% and 10%, respectively. The A_{eff} and the core NA of fibers used in the 2 kW fiber laser were 400 μm^2 and 0.07, respectively. For the single mode operation, we used an Yb-doped fiber with differential modal gain where Yb is doped only around the center of the core so as to obtain the greater gain of LP$_{01}$ mode than that of LP$_{11}$ mode. The absorption efficiency of the Yb-doped fiber was 0.67 dB/m. So we can shorten the fiber length of the Yb-doped fiber to 30 m which realizes sufficient absorption of the pump light. The length of the delivery fiber was 20 m. The total firer length is about 58 m including the laser cavity, delivery fiber, and other optical components.

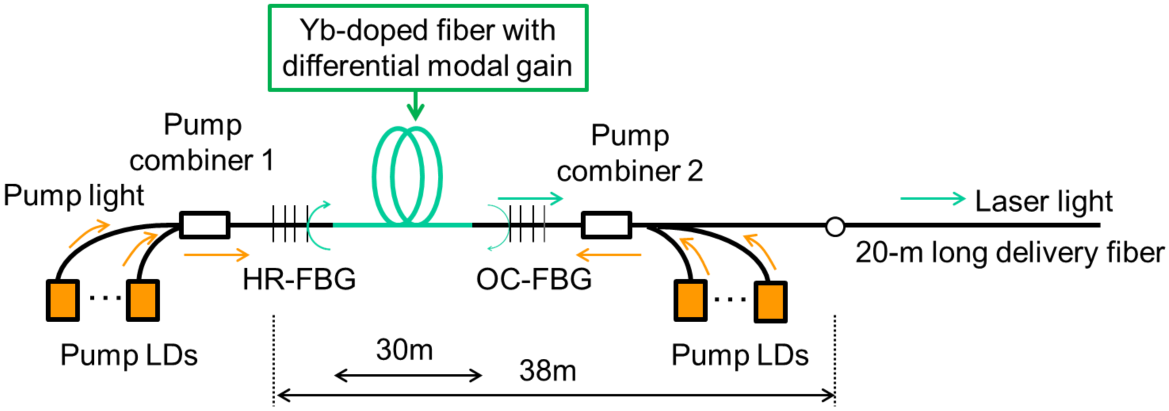

Figure 3. Schematic configuration of fabricated 2 kW single-mode fiber laser with a 20-m long delivery fiber.

4. EXPERIMENTAL RESULTS AND DISCUSSION

4.1 Output characteristics

Figure 4 shows the laser output power as a function of pump power. The output power reached 2 kW at a pump power of 2.86 kW. A slope efficiency was 70%. The beam profile at the focal point is also shown in figure 4. The M-squared factor was 1.2. Nearly diffraction-limited beam quality was obtained.

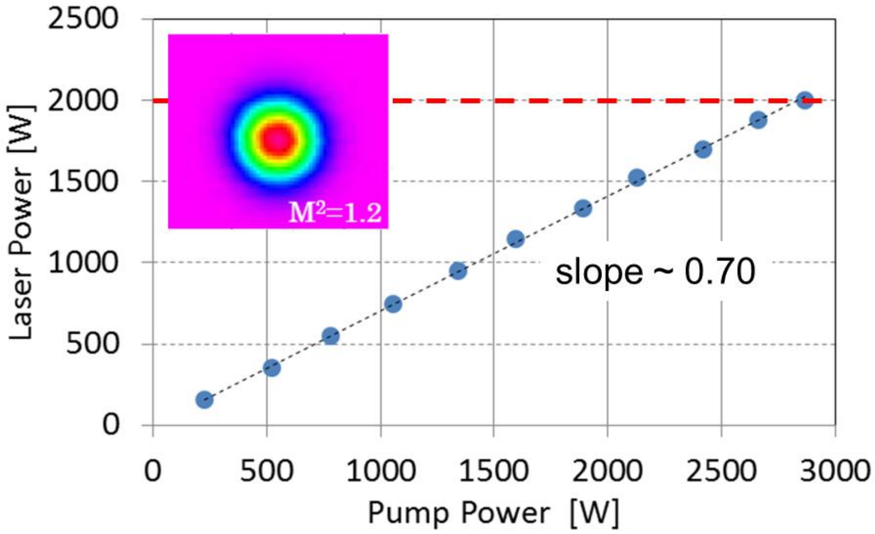

Figure 4. Laser output power versus pump power, and beam profile at focal point.

4.2 Output power spectrums

Figure 5 shows the measured output spectra at different laser output powers. No Stokes light by SRS was observed. The power ratio between the output power and the Stokes light was more than 50 dB when the laser output power was 2 kW even with a 20-m delivery fiber. The laser output power is only limited by the available pump power. So more output power will be achievable when introduce more pump power.

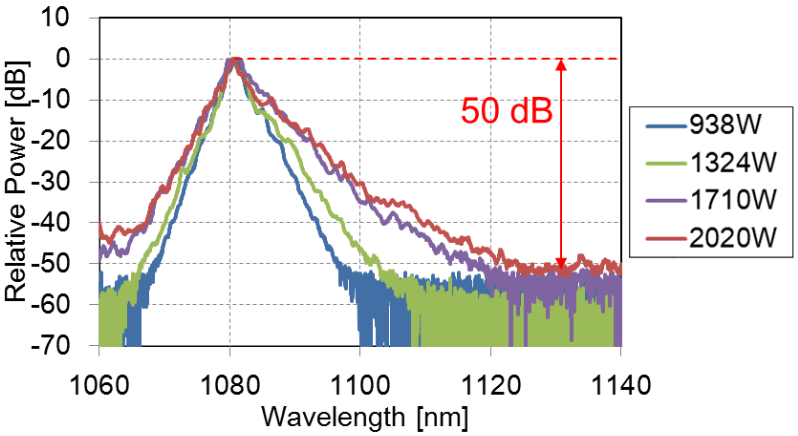

Figure 5. Laser output spectra for different laser output powers.

4.3 Estimation of raman gain

The power of Stokes light in the fiber laser is experessed as

$$\frac{dP_S(z)}{dz} = g_R \frac{P_P(z)}{A_{eff}(z)} P_S(z) - \alpha_S P(z) + C_{SR} P_P(z) \tag{4}$$

where g_R, $P_S(z)$, $P_P(z)$, $A_{eff}(z)$, α_S, C_{SR} are Raman gain coefficient of the fibers, the power of forward Stokes light at longitudinal position z, the sumation of forward and backward optical power at the lasing wavelength at position z, the effective a rea of the fundamental mode at position z, the attenuation coefficient of the Stokes light, spontaneous Raman coefficient, respectively. By solving equation (4) numerically we can estimate $P_S(z)$ if we know every parameter in the equation. $P_P(z)$ is given by solving the rate equation. $A_{eff}(z)$ and α_S are given by measuring the fiber parameters. g_R and C_{SR} can be roughly estimated by measuring SRS level of various fiber lasers. The Raman gain in the fiber laser is also calculated. As a result of calculation the one way small signal Raman gain is estimated as less than 40 dB when the output power of the fiber laser is 2.0 kW.

The SRS level is estimated to be less than 1 % of the fiber laser output when the output power is 3 kW. By using equation (3), we can expect the Raman threshold power P_{th} of 2.2 kW which is smaller than the experimental results. The reasons that we could realize a higher Raman threshold would be a relatively wide lasing band width of the fiber laser, a larger effective area of the beam due to existence of higher modes.

So far we have discussed the Raman threshold power where there is no reflection. If there is reflection from the workpiece or the delivery optics, the influence of the reflected light should be considered when the laser is used in a practical system as shown in Fig. 6. Because the Stokes light in the reflected light is highly amplified backward in the fiber laser.

If we allow 2 or 3 % fluctuation of laser output power when the output power is 2kW, the backward amplified SRS is also allowed to be approximately 50 W. Then back reflection power of the SRS light into the fiber core at the output end of the delivery fiber is allowed to be 5 mW since the Raman gain is 40 dB. That means 500 W back reflection of the fiber laser output is allowed. Because the SRS power is less than 5 mW which is -50 dB of 500 W. That means the laser works very stably even when the laser is irradiated onto a highly reflective material.

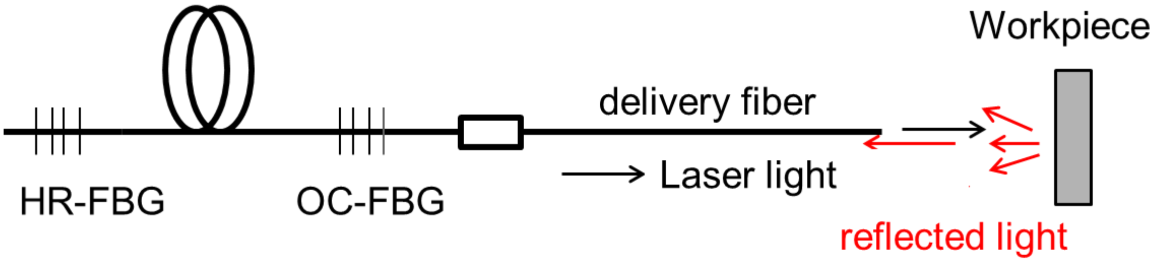

Figure 6. Schematic model of the fiber laser when considering back reflection.

5. SUMMARY

A 2 kw single-mode fiber laser with a 20-m long delivery fiber and high back reflection resistance has been demonstrated. The Stokes light power by SRS is more than 50 dB below the laser output power when the laser is operated at the output power of 2 kW even with a 20-m delivery fiber. Nearly diffraction-limited beam quality is also confirmed with the measured M^2 of 1.2.

From the experimental results and theoretical evaluation, an output power of 3 kw is believed to be achieved by increasing pump power. The output power fluctuation caused by SRS and back reflection in materials processing will be well suppressed. Our high power single-mode fiber lasers can provide high quality and stable processing of highly reflective materials.

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