10 kW Single Mode Fiber Laser with High Efficiency and SRS Suppression

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Fiber laser is becoming more popular in the processing field. In recent years, expectations for single mode fiber lasers with both high output and high beam quality have increased due to the possibility such as the expansion of processing targets and the energy transmission field. So far, we reported a single-mode fiber laser with an output of 8 kW. In this report, aiming for even higher output, we realized a 10 kW single-mode fiber laser with suppression of stimulated Raman scattering (SRS), high efficient and high beam quality.

1. Introduction

Fiber lasers have become widely utilized in fields such as metal cutting and welding due to their better beam quality and higher efficiency compared to solid-state lasers or CO_2 ones. Multi-mode fiber lasers, which are ease to increase output power, are mainly used in the metal processing market. On the other hand, single-mode fiber lasers are gaining popularity for processing challenging materials like CFRP and for innovative methods using galvanometer scanners, thanks to their superior beam quality. Additionally, single-mode fiber lasers are attracting attention for long-distance energy transmission. For example, the concept of Space Solar Power Systems (SSPS) [1] requires laser wireless power transmission to efficiently deliver energy to remote locations. Researches by JAXA, ESA, and NASA are exploring the feasibility of transmitting kilowatt-class power over several kilometers. Consequently, demand for high-efficiency, high-power, and high-beam-quality single-mode fiber lasers is increasing across various fields.

One of the challenges for achieving high-power single-mode fiber lasers is the suppression of stimulated Raman scattering (SRS). Raman scattering occurs when laser light interacts with optical phonon in the fiber, converting some of the laser light into unwanted Stokes light. Excessive SRS could cause output instability, leading to processing defects and potentially damaging the laser device.

We have been working on various technological developments to suppress SRS. For instance, we developed single-mode fiber lasers with extended delivery fiber lengths, considering their deployment in manufacturing environments, and with high processing performance for high-reflectivity materials[2)3)]. Furthermore, we achieved a single-mode fiber laser with an output power of 8 kW and an M^2 value of 1.3[4)], which serves as an index of beam quality. The laser development technology enabled us to apply it in various applications[5)]. Moreover, we demonstrated that CFRP cutting and drilling can be performed by combining our single-mode fiber laser with a commercially available galvanometer scanner, achieving high-speed and high-quality CFRP processing[6)]. In this paper, aiming for even higher output, we report the development of a single-mode fiber laser with an output power exceeding 10 kW, featuring suppression of stimulated SRS, high efficiency and high beam quality.

2. Configuration of 10 kW single-mode fiber laser

Figure 1 illustrates the schematic diagram of the constructed 10 kW single-mode fiber laser. The fiber laser is configured as a master oscillator power amplifier (MOPA) system, consisting of a master oscillator (MO) section and a power amplifier (PA) section. The MO section includes an ytterbium-doped fiber (YbDF), a high reflectivity fiber Bragg grating (HR-FBG), and an output coupler fiber Bragg grating (OC-FBG) that form a laser cavity. In the MO section, the pump light emitted from each laser diode modules (LDMs) is combined using a MO pump combiner and supplied to the optical cavity, generating a signal light. The PA section contains another YbDF, which amplifies the signal light input from the MO

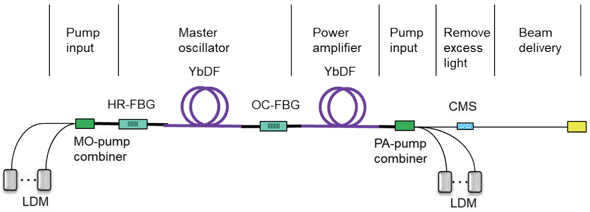

Fig. 1. Schematic diagram of the 10 kW single-mode fiber laser.

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Abbreviations, Acronyms, and Terms.

FBG—Fiber Bragg Grating
A fiber device that reflects paticular wavelength of light but transmits all others by a periodic variation in the refractive index of the core of optical fiber.

M^2—M square
A beam quality factor, which indicates how close the laser beam is to an ideal Gaussian beam. $M^2 = 1$ represents diffraction limit of beam and increase by deviation.

SRS—Stimulated Raman Scattering
When light is incident on a substance, light is modulated by lattice vibration of the substance to generate Stokes light (Raman scattering) which is a component of light whose frequency is shifted by the frequency component of photon vibration.
Stokes light is amplified in proportional to the light intensity when strong light is incident.

MOPA—Master Oscillator Power Amplifier
The most popular laser system in which a coherent beam of master oscillator (or seed light) is increased by power amplifier.

section by supplying a pump light from a PA pump combiner. The amplified signal light is processed to remove excess light in a cladding mode stripper (CMS) and then outputted from an output end through a beam delivery section.

As a method to suppress SRS in MOPA system, we adopted a structure in which the pump light of the MO section and the PA section traverses back and forth through the OC-FBG. The total fiber length of the fiber laser was shortened compared to the conventional MOPA configuration, by optimizing the Yb doping concentrations and lengths of the YbDFs both in the MO and PA sections. The LDMs used semiconductor laser diodes with an average output power of 300 W and a DC power-to-optical conversion efficiency of 50%. Additionally, a high wall plug efficiency (WPE) of the fiber laser system was achieved by choosing the pumping wavelength of 976 nm to improve absorption efficiency in the YbDF.

To suppress SRS, we designed a fiber with a large core diameter. Generally, the power of the Stokes light propagating in a fiber laser is represented by equation (1),

$$dP_s(z) = \left[\frac{g_R P_p(z) P_s(z)}{A_{eff}} - \alpha_S P_s(z) + g_{SR} P_p(z)\right] dz \quad (1)$$

where P_s is the power of the Stokes light, P_p is the power of the signal light, z is the longitudinal position in the optical fiber, g_R is the Raman gain coefficient, A_{eff} is the effective area of the propagating beam in the fiber, α_s is the attenuation of the Stokes light, and g_{SR} is the coefficient of spontaneous Raman scattering. Equation (1) suggests that using fiber with larger A_{eff} suppresses the Stokes light. Using equation (1), we calculated the power of the Stokes light when varying the parameter A_{eff}. As a result, by setting A_{eff} to 1000 μm^2, we have confirmed that achieving an output of 10 kW or more is possible, in combination with the shortened fiber length in the MOPA system.

On the other hand, since the larger core diameter leads to an increase in the number of propagating modes in an optical fiber, multimode beam propagation would result in degradation of beam quality. To mitigate the degradation of the M^2 value, it is important to design the fiber parameters appropriately and to improve the fusion splicing techniques between fibers.

Figure 2 shows the appearance of the fabricated laser device in this study. The dimensions are as follows: width (W) 710 mm × depth (D) 1100 mm × height (H) 1200 mm, which is approximately the same size as the multi-mode fiber laser device. Furthermore, the beam delivery length outside the laser device is set to 3.4 m, providing sufficient length for processing.

Fig. 2. Appearance of the 10 kW single-mode fiber laser.

3. Characteristics of the 10 kW single-mode fiber laser

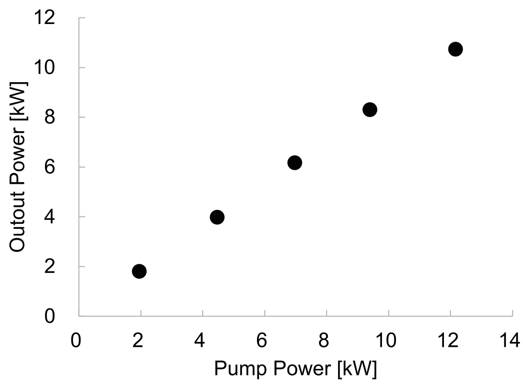

Fig. 3. Output characteristics of the fabricated fiber laser device.

Figure 3 shows the output characteristics of the fabricated laser device. When the total pump power to the MO and PA sections was 12.2 kW, the output power reached 10.7 kW, achieving a high output oscillation exceeding 10 kW.

Furthermore, the slope efficiency was as high as 87.4%. WPE at the output power of 10.7 kW was estimated to be 44.5%, indicating a highly efficient laser.

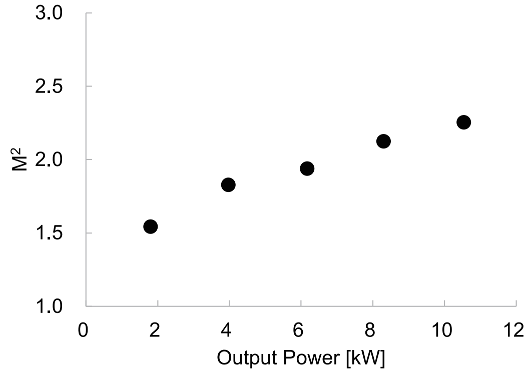

Fig. 4. Beam quality of the fabricated fiber laser device.

Figure 4 shows the beam quality of the fabricated fiber laser device. M^2 value was 2.25 at the highest output, achieving a high beam quality suitable for various applications.

However, the increase in M^2 value as increasing the output power indicates a degradation in beam quality. The deterioration in beam quality is believed to be caused by an increase in the number of propagation modes due to core diameter expansion. We will improve beam quality by optimizing the design parameters of the optical fiber.

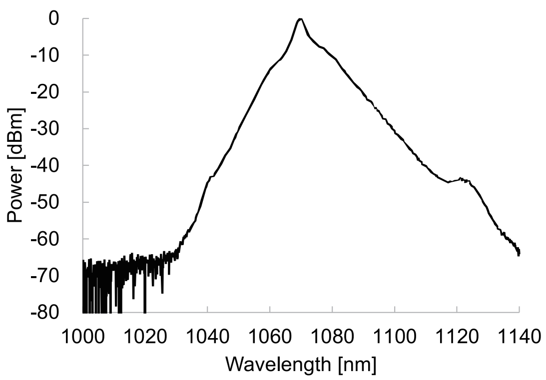

Fig. 5. Output spectrum at the laser output power of 10.7 kW.

Figure 5 illustrates the optical output spectrum of the fabricated laser device. The Stokes light occurred at a wavelength of approximately 1125 nm in response to the signal light with the lasing wavelength of 1070 nm. The power ratio of the output power to the Stokes light exceeds 40 dB, indicating that SRS was well suppressed even with an optical output power of higher than 10 kW.

Next, we tested the continuous operation of the laser device. Figure 6 shows the results of evaluating the output stability during a 10-minute continuous operation at an average output power of 11.0 kW. The power stability of output laser, measured after 35 seconds, which is the duration requiring the power measurement system to stabilize, of 0.14% demonstrated that the laser device achieved highly stable continuous operation. We can conclude that the fabricated laser device is capable of stable processing applications.

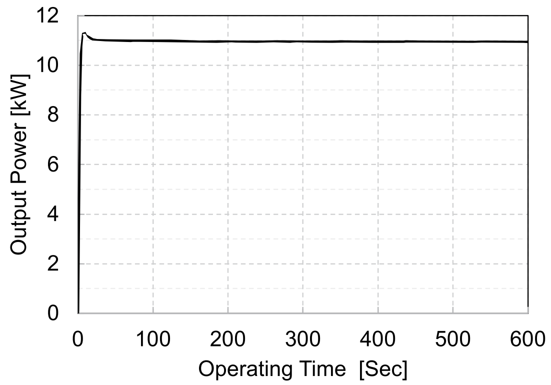

Fig. 6. Output power at 10 minutes of continuous operation.

4. Conclusion

In this paper, we achieved a high output power exceeding 10 kW and high beam quality by designing the laser configuration and fiber parameters to suppress SRS in single-mode fiber laser. In the future, we believe that our technologies, by further increasing the output power and improving the beam quality of single-mode fiber lasers, could make significant contributions to various industries and society.

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