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200-W Continuous-wave Thulium-doped All-fiber Laser at 2050 nm

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A 200-W continuous-wave thulium-doped all-fiber laser at 2050 nm was developed with a master oscillator power amplifier configuration. For the master oscillator, a single-mode thulium-doped fiber laser was built with fiber Bragg gratings. The operating power of the oscillator was 10.1 W at a pump power of 20.9 W, and the slope efficiency was measured to be 53.0%. All emitted wavelengths of the oscillator were located between 2049.2 nm and 2049.9 nm, and no other peaks in different wavelength ranges were observed. The maximum output power of the final amplified beam was 204.6 W at a pump power of 350.4 W. The slope efficiency of the amplifier was measured to be 58.4%.

Keywords : Fiber laser, High-power laser, Thulium laser
OCIS codes : (140.3460) Lasers; (140.3480) Lasers, diode-pumped; (140.3510) Lasers, fiber

I. INTRODUCTION

High-power 2-μm-wavelength lasers have been attracting interest as eye-safe lasers for scientific research and industrial technology. Because the 2-μm wavelength is located in the atmospheric window, it can be employed as a light source for light detection and ranging (LIDAR) or gas-sensing systems [1–6]. A 2-μm laser can also be used as a pump source for other lasers, and in medical surgery, industrial material processing, and optical communication [1–4, 6–10].

The 2-μm wavelength is typically generated with a thulium-doped laser. Among various laser types, the thulium-doped fiber laser (TDFL) has many advantages. As a fiber laser, it is compact, efficient, stable, and has excellent beam quality compared to bulk lasers. For this reason, TDFLs have been being actively developed by many researchers [1–16]. TDFLs are commonly pumped by 790-nm laser diodes (LDs). In some studies, a tandem-pumping method has been employed to reduce the thermal load generated in the active medium, using a second 1.9-μm thulium-doped laser as the pump source instead of 790-nm LDs [15, 16]. However, this configuration has not been widely used because of its complexity. Most TDFLs reported to date are pumped by 790-nm LDs.

Despite the cross-relaxation processing [17], where two laser photons can be generated from one pump photon, a large thermal load is created in the 790-nm pumped TDFL, making it difficult to scale up the output power. To address this, researchers have developed their own technology to overcome the thermal load for high-power TDFLs [1–14]. The maximum power for the 790-nm pumped TDFL reported to date is 1 kW [11], and high-power TDFLs of tens to hundreds of watts have been steadily developed [1–10, 12–14].

With reference to these previous works, we have also been developing a high-power 790-nm-pumped TDFL as an ionizing light source for application in lithium-isotope separation. The final goal of our application is to obtain a high-quality 2050-nm laser beam at a power level of 500 W or 1 kW. As the first step toward our goal, a 200-W continuous-wave TDFL has been developed in this work. With careful treatment of the fiber connection, we have achieved a power of 200 W at 2050 nm in an all-fiberized structure.

II. EXPERIMENTAL SETUP

The 2050-nm, 200-W continuous-wave TDFL was con-

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structed with a master oscillator power amplifier (MOPA) configuration. For our application, the output laser did not need to have a very narrow linewidth. Therefore, a seed-laser source with a narrow linewidth like a distributed feedback (DFB) LD was not required. A master oscillator was built as a single-mode TDFL with fiber Bragg gratings (FBGs); it was designed to emit a 2050-nm laser beam with a power level of about 10 W. Following the oscillator, one thulium-doped fiber amplifier was applied to amplify the seed beam and yield an output power of about 200 W.

Figure 1 shows the scheme of the master oscillator in the 200-W TDFL. In the oscillator, a single-mode double-clad thulium-doped fiber (Nufern, CT, USA) with a core diameter of 10 μm, a cladding diameter of 130 μm, and a core numerical aperture (NA) of 0.15 was applied as the active medium. It had a length of 5 m and was spliced on both sides with matched passive fibers. For cooling, a portion of the thulium-doped fiber was wound in a grooved cylinder of aluminum alloy with a diameter of 100 mm. No treatment was performed between fiber and cylinder.

To construct the resonator, FBG components were spliced to both sides of the thulium-doped fiber module. A high-reflective FGB (HR-FBG; TeraXion, Quebec, Canada) with 99.8% reflectance at 2050 nm and a low-reflective FBG (LR-FBG; TeraXion, Quebec, Canada) with 9.3% reflectance at 2050 nm were applied as the rear mirror and output coupler respectively. The FBGs were designed to have a laser-output linewidth on the order of 1 nm. The reflection bandwidths of the HR-FBG and LR-FBG were designed to be 3.0 nm and 1.0 nm respectively.

A 793-nm LD (BWT ltd., Beijing, China) with a maximum power of 30 W was used as the pump source . The pump light from the LD was emitted through a coupled fiber having a core diameter of 105 μm and a core NA of 0.22. This coupled fiber was spliced directly behind the HR-FBG, so that the pump light could be transmitted through the FBG and absorbed in the thulium-doped fiber. The loss of pump light in the HR-FBG was less than 1%.

Figure 2 shows the entire scheme of the MOPA system of the 200-W TDFL. A fiber optical isolator (FOI) and a

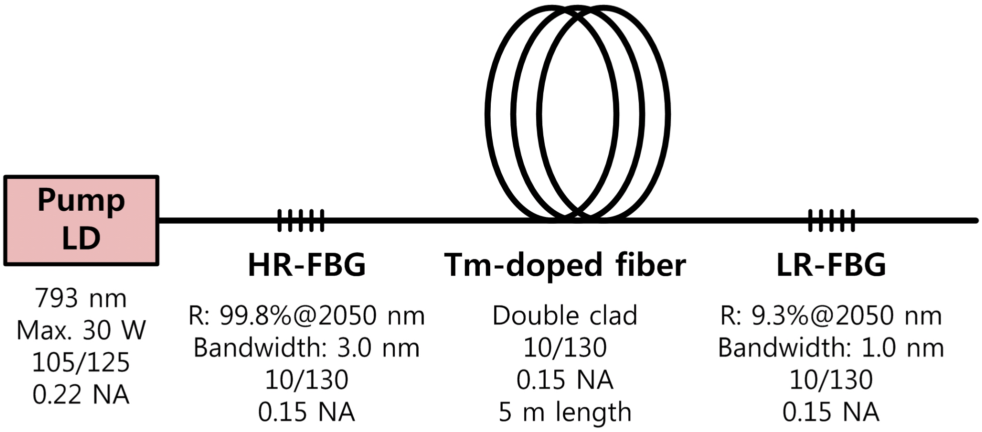

FIG. 1. Scheme of the master oscillator in the 200-W TDFL. LD, laser diode; HR-FBG, high-reflective fiber Bragg grating; LR-FBG, low-reflective fiber Bragg grating.

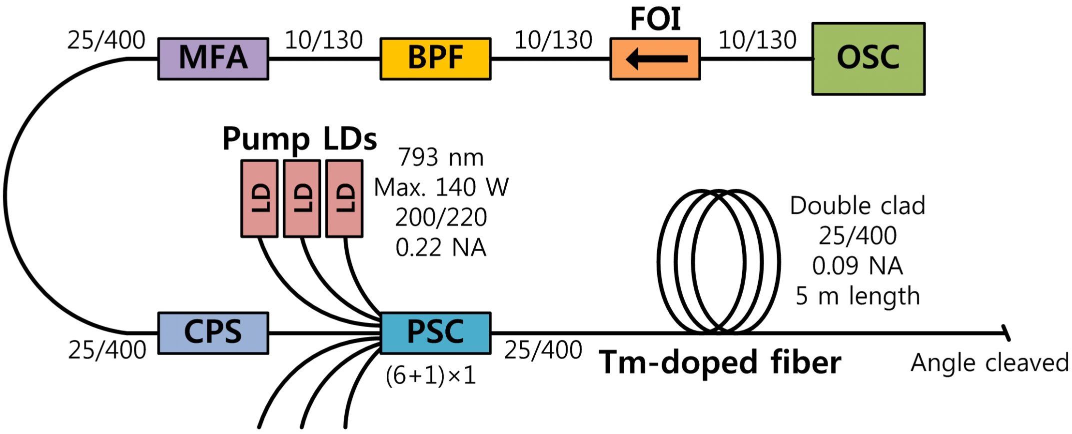

FIG. 2. The entire scheme of the MOPA system of the 200-W TDFL. OSC, oscillator; FOI, fiber optical isolator; BPF, band-pass filter; MFA, mode-field adapter; CPS, cladding power stripper; PSC, pump and signal combiner; LD, laser diode.

band-pass filter (BPF) were located after the oscillator, to cut off the back reflection from the following amplifier. The FOI (Haphit, Wurzburg, Germany) was a polarization-insensitive isolator operated at 2050 nm, and the maximum allowed power was 10 W. A BPF (Haphit, Wurzburg, Germany) with a pass-band center wavelength of 2050.80 nm and a pass-bandwidth of 6.40 nm at −0.5 dB was applied. Like the FOI, the maximum allowed power of the BPF was 10 W. After the BPF, large-mode-area fibers were used, and the size of the fiber was increased to a core diameter of 25 μm and a cladding diameter of 400 μm. The mode-field adapter (MFA; ITF Technologies, Quebec, Canada) was employed after the BPF, to match the mode field between the single-mode and the large mode area fibers. A home-made cladding power stripper (CPS) was applied after the MFA, to remove the residual pump light from the oscillator and back-reflected pump light from the amplifier.

The amplifier was located at the last stage of the MOPA system. In the amplifier, a large-mode-area double-clad thulium-doped fiber (Nufern, CT, USA) with a core diameter of 25 μm, a cladding diameter of 400 μm, and a core NA of 0. was applied as the active medium. It had a length of 5 m and was spliced on both sides with the matched passive fibers. As in the oscillator, a portion of the thulium-doped fiber was wound in a grooved cylinder of aluminum alloy. The outer diameter of the cooling cylinder of the amplifier was 200 mm. Since the thermal load was much larger than that of the oscillator, this cylinder was bonded to a water-cooled heat sink held at 25 °C. In addition, a contact material was needed to improve the thermal contact between fiber and cylinder surface. As a contact material, a diamond thermal paste was filled into the grooves before winding, so that the generated heat could be transferred well from fiber to cylinder. After winding the fiber around the cylinder, the thermal paste was additionally applied on the area where heat was generated most.

In the amplifier, three 793-nm fiber-coupled LDs (Hans TCS, Beijing, China) with a maximum power of 140 W were used as the pump sources. The coupled fiber of each LD had a core diameter of 200 μm and an NA of 0.22. A (6 + 1) × 1 pump and signal combiner (PSC; Lightcomm, Shenzhen, China) was applied to combine the pump light from the three LDs. The maximum output power of the combined pump light was measured to be 366.3 W. The pump light was absorbed in the thulium-doped fiber, and the seed beam was amplified. The amplified output laser was finally emitted through the angle-cleaved fiber.

In configuring the amplifier, careful treatment was required in the connection of the fibers to prevent damage to them by heat generation. The pump power of the amplifier was high, so even a small amount of pump-light loss in the splicing or recoating area caused the temperature to rise due to heat generation. In particular, since more heat was generated where the thulium-doped fiber started, even a slight loss caused damage to the splicing area between the thulium-doped and passive fibers. Therefore, low-loss splicing conditions and careful cleaving and recoating were essential. For double-clad large-mode-area fibers, it took a lot of effort to find this condition. After many trials, we finally found an optimal splicing condition, and all fibers in the amplifier were spliced to this condition.

III. RESULTS AND DISCUSSION

Prior to connecting the amplifier, we measured the output characteristics of the master oscillator. For the measurement, the fiber emitting the oscillator output beam after the LR-FBG was angle-cleaved. Figure 3 shows the output power versus the pump power in the master oscillator. The obtained maximum output power was 15.1 W at a pump power of 29.9 W. The output power of the oscillator was limited by the maximum emitted power of the pump LD. As shown in Fig. 3, the slope efficiency of the oscillator was measured to be 53.0%. Compared to other references with 790-nm pumping [1–14], this value seemed quite typical. Even though there was no treatment between the fiber and the cooling cylinder, no problem occurred, even when running at full power for a long time. The highest surface temperature of the thulium-doped fiber, which was measured using a thermal camera (FLIR, OR, USA), was kept below 95 °C.

Figure 4 shows the output spectra of the master oscillator, measured with an optical spectrum analyzer (Thorlabs, NJ, USA). As shown in Fig. 4, 12 spectral curves were obtained at different times. The shape of the spectrum continued to change during lasing, with the number of peaks varying from 1 to 3. This means that the resonance condition of the oscillator changed over time. Since FBGs with nanometer-order reflection bandwidths were used for resonance and no treatment was performed to obtain a narrower

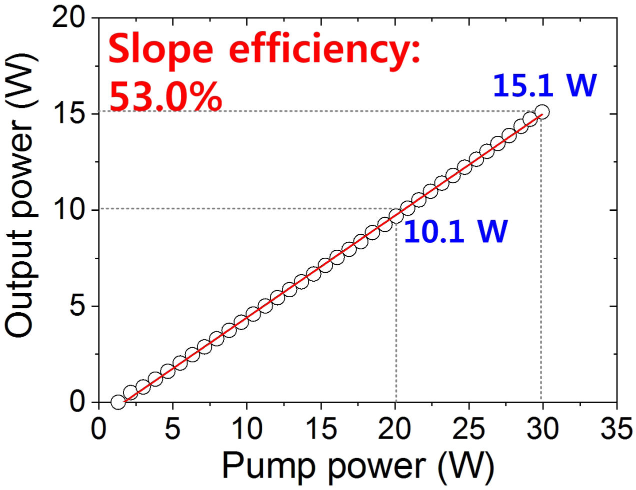

FIG. 3. Output power versus pump power in the master oscillator. The obtained maximum output power was 15.1 W at a pump power of 29.9 W. The operating power of the seed laser used for amplification was set to 10.1 W.

spectrum with a single peak, the resonance conditions could change over time due to the influence of environmental changes, such as temperature variation. However, all emitted wavelengths were located between 2049.2 nm and 2049.9 nm, and no other peaks in different wavelength ranges were observed. Also, since we were not aiming for a narrow linewidth, this variation was not of particular concern.

After measuring its output characteristics, the master oscillator was connected to the next stage. Although the oscillator could be stably operated at maximum output for a long time, it had to be driven at a level of 10 W, because the maximum allowable output of the subsequent FOI and BPF was limited to 10 W. Thus, the operating power of the oscillator used as a seed laser for amplification was set to 10.1 W, and the pump power was 20.9 W at this time. The power fluctuation of the seed laser measured for 25 minutes was 0.62% (as a standard deviation). The seed-laser power incident upon the amplifier was reduced by about half compared to the value immediately after the oscillator, due to the losses in the subsequent optical components. After passing through the FOI and BPF, the power of the seed laser decreased to 6.7 W, and after passing through the MFA and CPS it was further reduced to 5.7 W. Nevertheless, an output power of 200 W could be achieved through amplification.

Figure 5 shows the output power versus the power of the pump light in the amplifier. The maximum obtained output power was 204.6 W at a pump power of 350.4 W. Although the maximum achievable pump power from the LDs was 366.3 W, the pump power was not increased further, because it already achieved the 200-W level at a pump power of 350.4 W. As shown in Fig. 5, the slope efficiency of the amplifier was measured to be 58.4%. The spectral characteristics were the same as those of the oscillator, with no significant differences.

The surface temperature of the fibers was also checked during amplification. The highest surface temperature of the thulium-doped fiber could not be accurately measured, because the diamond thermal paste covered the thulium-doped fiber; only the temperature of the surface of the thermal paste could be measured. Up to a pump power of 350.4 W, the temperature of the thermal paste rose to approximately 76 °C. By inference from this temperature, the surface temperature of the thulium-doped fiber would be much higher. Heat was also generated between the connections of the passive fibers, due to pump-power loss at the splicing points. The part that generated the most heat was the connection right after the PSC, where the temperature rose to 92 °C despite careful efforts in splicing and recoating.

Since we aimed only to achieve an output of 200 W in this work, we did not measure the beam quality. For a fiber with a core diameter of 25 μm and a NA of 0.15, the V number, which indicates the number of modes in a step-index fiber [18], was calculated to be 5.747. This means that the fiber used in the amplifier did not have a single mode. Since no method was applied to suppress multiple modes in the amplifier, the output beam had several modes mixed together. As a result, the quality of the output beam would be poor and the M^2 factor much larger than the final target of approximately 1.

Also, mode instability is expected to occur as a result of small environmental changes. Therefore, additional techniques are required to achieve a single-mode, high-quality, stable beam close to an M^2 factor of 1. The tight-coiling method is one way to achieve a single-mode beam, by suppressing multimode generation [2, 3, 8]. In our case the fiber of the amplifier was coiled into the cooling cylinder with a relatively large diameter of 200 mm. If the fiber were coiled with a smaller diameter, single-mode operation would be possible.

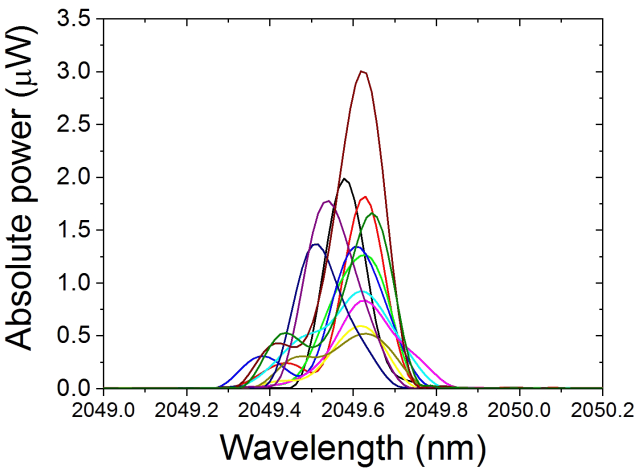

FIG. 4. Output spectra of the master oscillator. The 12 spectral curves were measured at different times during lasing. All peaks were located between 2049.2 nm and 2049.9 nm.

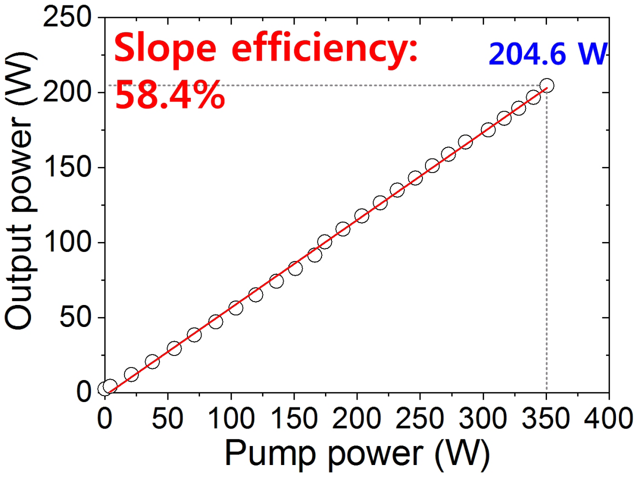

FIG. 5. Output power versus the pump power in the amplifier. The maximum obtained output power was 204.6 W at a pump power of 350.4 W.

IV. CONCLUSION

In summary, we developed a 200-W continuous-wave TDFL, which was constructed with a MOPA configuration. For the master oscillator, a single-mode TDFL with FBGs was built. The operating power of the oscillator was 10.1 W at a pump power of 20.9 W. The slope efficiency of the oscillator was measured to be 53.0%, and no thermal problem occurred, even after running for a long time. Looking at its spectra, all emitted wavelengths were located between 2049.2 nm and 2049.9 nm and no other peaks were observed. The final output laser was obtained after amplification of the seed beam from the oscillator. The maximum output power of the amplifier was 204.6 W at a pump power of 305.4 W. The slope efficiency of the amplifier was measured to be 58.4%.

Despite achieving 200 W of output power in our TDFL in the first step, thermal problems still remain before further scale-up to the 500-W or 1-kW level to reach our final development goal. It will be important to carefully analyze the splicing and recoating conditions, to minimize the pump power loss. If that problem is not solved, even after improving the loss at fiber-to-fiber junctions it may not be possible to solve the thermal problem, which occurs within the thulium-doped fiber itself. In that case, immersing the entire amplifier module in a water basin might be a way to solve the thermal problem.

In addition to solving the thermal problem, achieving a high-quality laser beam with an M^2 factor close to 1 remains as another challenge. As mentioned, it is expected that this can be achieved using the tight-coiling method. However, due to the risk of breaking the fiber, the coiling diameter cannot be significantly reduced. The spliced area is the most vulnerable to breakage. Therefore, in the future we will have to determine the proper coiling diameter that will not break the fiber, but will suppress multiple modes well.

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