Highly efficient high-power thulium-doped germanate glass fiber laser

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A 64 W fiber laser at 1.9 μm with a slope efficiency of 68% with respect to the launching pump power at 800 nm was demonstrated in a one-end pump configuration using a piece of 20 cm long newly developed thulium-doped germanate glass double-cladding single-mode fiber. A quantum efficiency of 1.8 was achieved. An output laser power of 104 W at 1.9 μm was demonstrated from a piece of 40 cm long fiber with a dual-end pump configuration.

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High-power fiber lasers have generated a significant amount of interest in recent years. Highly efficient and high-power fiber lasers at 1 μm with output powers greater than 1 kW were demonstrated from ytterbium-doped silica fiber.[1–3] Slope efficiency is typically around 70%. These highly efficient high-power fiber lasers are being used for many industrial applications, especially in material processing. A high-power fiber laser at 1.5 μm is of great interest because of the availability of components at this wavelength and, more important, because it is a retina safe wavelength. An output power of 188 W at 1.57 μm was demonstrated from an erbium and ytterbium codoped silica glass fiber laser.[4] The typical slope efficiency of the erbium and ytterbium codoped fiber laser at 1.5 μm was smaller than 45% because of the large difference between the pump wavelength and laser wavelength.

A thulium-doped fiber laser near 2 μm is also of great interest because of the possibility of combining high efficiency, high output power, and retina safety in addition to specific applications associated with this wavelength, such as remote sensing and biomedical applications. Thulium exhibits a significant advantage over other rare-earth ions in that the slope efficiency can exceed the Stokes limit.[5–7] A quantum efficiency near 2 can be achieved for thulium ions' $^3F_4 \rightarrow {}^3H_6$ transition (near 2 μm) because of the so-called cross-relaxation energy transfer between thulium ions. During the cross-relaxation energy transfer process, two ground-level thulium ions can be excited to the upper lasing level of the $^3F_4 \rightarrow {}^3H_6$ transition by absorbing only one pump photon near 800 nm, which means one excited Tm^{3+} ion at the $^3H_4$ level generates two Tm^{3+} ions at the $^3F_4$ upper laser level. The high doping concentration is critical to realize efficient cross-relaxation energy transfer.[8] A 75 W cw 2 μm laser was demonstrated from a 2.5 m long ytterbium-sensitized thulium-doped silica fiber.[9] The pump laser at 975 nm was absorbed by the ytterbium ion and then transferred to the $^3H_5$ energy level of the thulium ion. The slope efficiency of the laser with respect to the launched power is 32% owing to the lack of cross-relaxation energy transfer between thulium ions in ytterbium-sensitized thulium-doped fiber. Apparently, to achieve the most efficient high-power thulium-doped fiber laser, approximately 800 nm is the best pump wavelength that can make the one-for-two cross-relaxation energy transfer occur. To date, the most efficient Tm^{3+}-doped fiber laser reported is from a piece of 2.2 wt. % Tm^{3+}-doped silica fiber directly pumped by 800 nm laser diodes. The slope efficiency of 61% with respect to the launched power was demonstrated with an output power of 30.8 W.[6] The published highest power of a Tm-doped fiber laser is 85 W, generated from a Tm^{3+}-doped fiber laser under a 793 nm pump.[10] In this Letter we present a 64 W fiber laser at 1.9 μm with a slope efficiency of 68% with respect to the launching pump power at 800 nm in a one-end pump configuration using a piece of 20 cm long newly developed thulium-doped germanate glass double-cladding single-mode fiber, and we present a 104 W fiber laser at 1.9 μm from a piece of 40 cm long dual-end pumped fiber.

The core glass, 4 wt. % Tm^{3+}-doped germanate glass, and cladding glasses were developed and melted in house. Tm^{3+}-doped germanate glass double-cladding single-mode fibers were designed and fabricated in house as well. The low phonon energy of the germanate glass host compared with silica glass helps to increase the quantum efficiency and reduce the nonradiative decay rate of the upper lasing level of $^3F_4$. The high doping concentration of thulium ions ensures cross-relaxation energy transfer by bringing the thulium ions closer. The emission spectrum of a bulk 4 wt. % Tm^{3+}-doped germanate glass under 800 nm laser excitation is shown in Fig. 1. The emission of the $^3H_4 \rightarrow {}^3F_4$ transition, which is usually used as emission source for an S-band laser and amplifier at 1.47 μm, can hardly be observed. The quenching of emission at 1.47 μm indicates that the transition between $^3H_4$ and $^3F_4$ states was dominated by the nonradiative decay caused by cross-relaxation energy transfer, which was used to determine the optimum doping concentration of our Tm^{3+}-doped germanate core glass. The same core glass composition was used to fabricate Tm^{3+}-doped germanate glass single-mode fiber for the recent demonstration of an efficient single-frequency fiber laser near 2 μm.[11]

Two fibers with different core diameters but the same glasses were prepared for fiber laser demonstrations. The core diameters are 50 and 42 μm. Both of them have a 200 μm inner cladding. The numerical aperture (NA) of the core is 0.02 according to the refractive indices of bulk glasses. The V-numbers of these two fibers at 1.9 μm are 1.96 and 1.65, respectively, thus supporting only the fundamental mode at the lasing wavelength. Instead of the commonly used polymer, low-index glass was used as the outside cladding material in the high-power silica fiber. Because of the large core diameter, the core and inner cladding area ratio is relatively large for both fibers, which leads to a large overlap between the core and the pump laser. Such a fiber configuration ensures efficient pump absorption and shortens the length of the active fiber. A short fiber length can be advantageous to avoid optical nonlinearity.

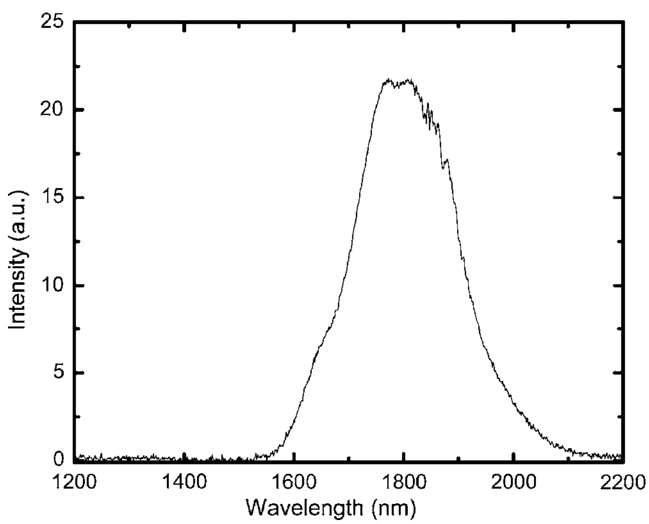

Fig. 1. Emission spectrum of 4 wt. % doped germanate glass.

The experiment setup for the one-end pump configuration is shown in Fig. 2(a). A piece of 20 cm long Tm^{3+}-doped germanate glass double-cladding fiber with a 50 μm core diameter was placed between two water-cooled metal plates in a sandwich structure. Both ends of the doped fiber were polished. A multimode fiber with a core diameter of 200 μm and NA of 0.22 was used as the pump delivery fiber. The wavelength of the pump laser (Apollo Instruments) is 800 nm. One end of a commercial multimode fiber, the same as the pump delivery fiber, was coated with a dichroic thin film with high reflectivity at 1.9 μm and high transmission at 800 nm, and the other end was fusion spliced with the pump delivery fiber. The fusion-spliced pump delivery fiber was butt coupled to the Tm^{3+}-doped fiber, and the dielectric coating served as the high-reflection (HR) mirror of the fiber laser cavity. Fresnel reflection of approximately 5% from the other polished end of the Tm^{3+}-doped germanate glass fiber functioned as the partially reflective mirror of the laser cavity. The experimental result for the fiber laser is shown in Fig. 3. We used the launching power instead of the launched power in the laser output curve. The launching power is defined as the power measured right after the pump laser delivery fiber. The maximum output power of the fiber laser is 64 W, which was limited by the available pump laser power. The slope efficiency is 68% with respect to the launching power, which is significantly higher than the Stokes limit of 42%. The slope efficiencies of the fiber laser with respect to the launched power and the absorbed power are estimated to be 71.6% and 76.4%, respectively. To the best of our knowledge, this is the most efficient fiber laser near 2 μm. The quantum efficiency is estimated to be 1.8, which is consistent with our previous experimental results.[7,12]

To achieve higher output power, another fiber coupled diode laser (Limo GmbH) was used to pump Tm^{3+}-doped germanate glass fiber from the other end. The second pump was launched into the Tm^{3+}-doped fiber by using free-space coupling lenses

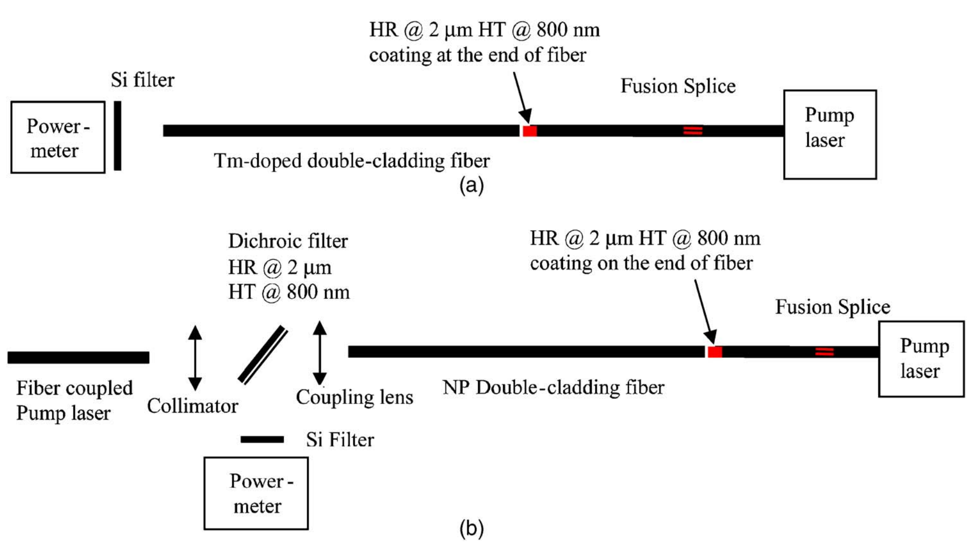

Fig. 2. (Color online) Schematic of thulium-doped germanate fiber laser experiment setup. (a) One-end pump configuration. (b) Dual-end pump configuration. HR, high reflection; HT, high transmission.

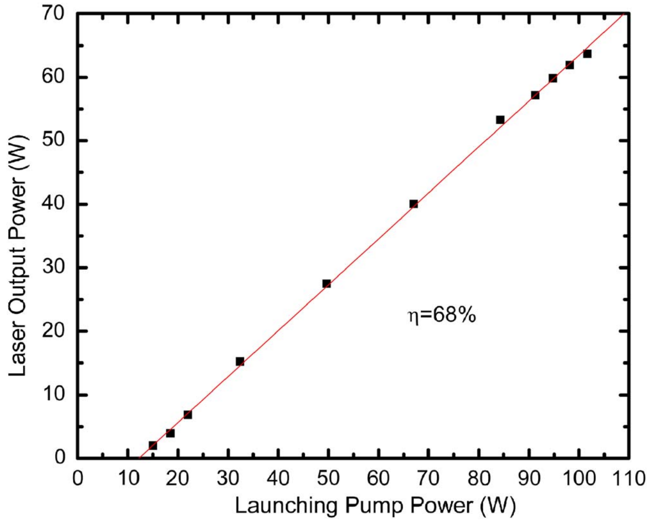

Fig. 3. (Color online) Laser output power versus launching pump power. The slope efficiency is 68% with respect to the launching power.

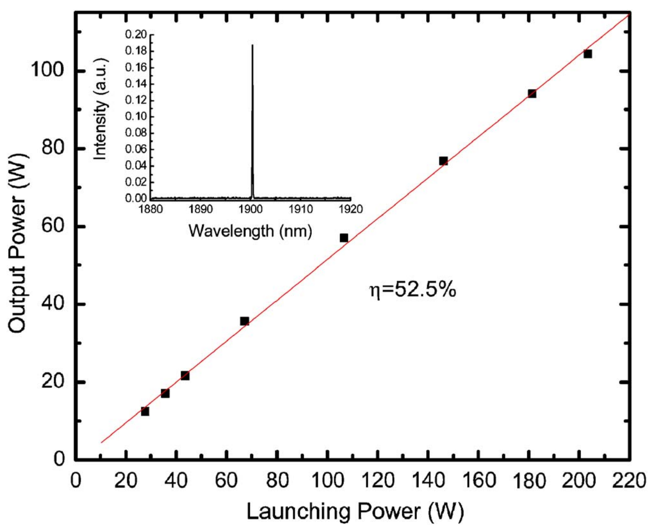

Fig. 4. (Color online) Dual-end pump laser result. The inset shows the laser spectrum.

as illustrated in Fig. 2(b). Both pump diodes were turned on simultaneously. A piece of 40 cm long germanate glass double-cladding single-mode fiber with a 42 μm core diameter is used in the dual-end pump demonstration. The output power curve of the fiber laser is shown in Fig. 4. Because of the lack of antireflection coating on the pump coupling lenses, a fair amount of pump power and output laser power were lost as a result of the surface reflections. The transmission of the 1.9 μm lasers coupling lens was measured as 78%. We compensated the laser power for the transmission loss of the coupling lenses for both pump power and output laser power in Fig. 4. The maximum output power of the fiber laser is 104 W. To the best of out knowledge, this is the highest output power of a thulium-doped fiber laser pumped near 800 nm. Because of the higher gain along the fiber in the dual-end pump configuration, it has a lower pump threshold than the one-end pump laser. The inset of Fig. 4 shows the spectrum of the fiber laser. The laser wavelength is 1.90 μm, which is 100 nm longer than the emission peak in the bulk sample. The slope efficiency of the output power of the fiber laser is 52.5% with respect to the launching pump power, which can be significantly improved by optimizing the fiber length and coupling optics. A relative long fiber is used for the dual-end pump configuration to ensure that the power from one pump coupling into the other pump is sufficiently low to prevent laser-induced damage.

In summary, we have demonstrated a highly efficient 1.9 μm fiber laser by using our newly developed highly thulium-doped germanate glass double-cladding single-mode fiber. The highest slope efficiency of the fiber laser reaches 68% with respect to the launching power from a piece of 20 cm long fiber by using a one-end pump configuration. An output laser power of 104 W at 1.9 μm was achieved from a piece of 40 cm long dual-end pumped fiber, which is scalable with higher pump power. Our results indicate that a highly efficient high-power thulium fiber laser near 2 μm is a promising laser source in the eye-safe wavelength range for a variety of applications.

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