

Efficient operation of diode-pumped single-frequency thulium-doped fiber lasers near $2\ \mu\text{m}$

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Efficient operation of diode-pumped single-frequency fiber lasers at wavelengths from 1740 to 2017 nm has been demonstrated by using a very short piece of newly developed single-mode active fiber, i.e., heavily thulium-doped germanate glass fiber. At 1893 nm, the single-frequency fiber laser has a pump threshold of 30 mW, a slope efficiency of 35%, and maximum output power of 50 mW with respect to the launched power of single-mode pump diodes at 805 nm. To the best of our knowledge, this is the highest lasing efficiency achieved in single-frequency fiber lasers operating near $2\ \mu\text{m}$. Frequency noise of the single-frequency fiber laser at 1893 nm has been characterized and compared with that of single-frequency fiber lasers at 1 and $1.55\ \mu\text{m}$. © 2007 Optical Society of America
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Coherent laser sources with single-frequency narrow-linewidth output are required for many applications. Diode-pumped single-frequency solid-state lasers (e.g., monolithic nonplanar Nd:YAG ring oscillator laser) have been the well-known low-noise coherent laser sources with a spectral linewidth ranging from hundreds of kilohertz to as narrow as a few kilohertz for two decades. Recently, much attention has been given to the development of diode-pumped single-frequency fiber lasers because these fiber-based lasers not only provide alternative highly coherent light sources, but also offer multiple wavelength regions at 1, 1.5, and $2\ \mu\text{m}$ (Refs. 1–3) and many unique advantages over conventional solid-state lasers in terms of reliability, ruggedness, and compactness. The wide ranges of operating wavelengths of fiber lasers provide the flexibility for those applications where operation wavelength is vital, such as laser spectroscopy, remote sensing, and coherent laser seeding application.

Laser action near $2\ \mu\text{m}$ based on Tm^{3+} ions has attracted intense interest for two decades for its wide applications in medicine, lidar, and materials processing.^{4–6} Due to the so-called cross-relaxation process, efficient $2\ \mu\text{m}$ laser operation (on the 3H_4 – 3H_6 transition) has been achieved in Tm^{3+} -doped crystals by using the 3F_4 – 3H_6 pump transition of Tm^{3+} near 800 nm. The Tm^{3+} cross-relaxation is a nonradiative process in which a single excited Tm^{3+} ion in the 3H_4 level generates two Tm^{3+} ions in the 3F_4 upper laser level, potentially yielding 200% quantum efficiency for $2\ \mu\text{m}$ laser operation.⁵ Experiments with Tm^{3+} -doped crystals indicate that the probability of the Tm^{3+} cross relaxation is very dependent on the doping concentration. The probability is negligible at low doping concentration (<2 wt. %) but it approaches unity (200% quantum efficiency) at high concentration (~ 5 wt. %) that make the laser extremely efficient.

The same laser action can be achieved in Tm^{3+} -doped fiber.⁷ In Tm^{3+} -doped silica glass fiber lasers, however, their efficiency is unfortunately not so high. First, the cross-relaxation process is limited in the fiber lasers because high Tm^{3+} doping concentration is restricted in silica glass. Second, silica glass is not an ideal host for the $2\ \mu\text{m}$ laser transition because of the high phonon energy ($1100\ \text{cm}^{-1}$) of the silica glass network, which can significantly quench the upper laser level and dramatically lower the quantum efficiency. As a result, the output power and the quantum efficiency of Tm^{3+} silica fiber lasers are quite limited. For instance, the first report on single-frequency distributed feedback (DFB) Tm^{3+} -doped silica fiber laser that was pumped with a Ti:sapphire laser at 790 nm showed that it is less efficient³ (1 mW maximum output at 1735 nm and 0.2% slope efficiency). Another silica-based DFB fiber laser recently also reported a poor efficiency (5 mW maximum output at 1836 nm and 1% slope efficiency) that was in-band pumped at 1565 nm.⁸ Recently, however, we have achieved a highly efficient $1.9\ \mu\text{m}$ laser operation using heavily Tm^{3+} -doped germanate glass fiber with reported 180% quantum efficiency.⁹ The high efficiency was attributed to the efficient cross-relaxation process and the low phonon energy ($900\ \text{cm}^{-1}$) in the heavily doped germanate glass. In this Letter, we report the first diode-pumped single-frequency fiber laser operation near $2\ \mu\text{m}$ using the heavily Tm^{3+} -doped germanate fiber,¹⁰ whose efficiency is much higher than those silica-based Tm^{3+} -doped DFB fiber lasers. The frequency noise of the diode-pumped single-frequency fiber laser at 1893 nm has been measured and compared with the data for single-frequency fiber lasers at 1550 and 1064 nm, whose heterodyne linewidth has been well characterized to be 3 kHz (Refs. 1 and 2).

The single-mode germanate glass fiber with 5 wt. % Tm_2O_3 doping concentration that was fabri-

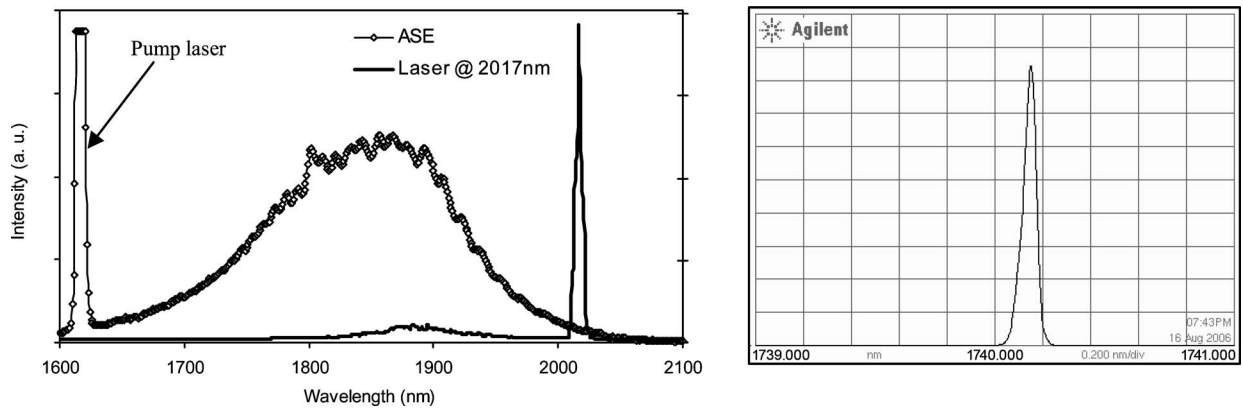


Fig. 1. Left, forward ASE spectra (and pump laser with open circles) and laser spectra at 2017 nm (solid curve) recorded by using a monochromator and a cooled InAs detector. Right, laser spectra at 1740 nm recorded by an optical spectrum analyzer¹¹ (Agilent 86140B).

cated in-house was used in the experiment. The numerical aperture of the fiber is 0.15, while the core diameter and outer diameter of the fiber are 7 and 125 μm , respectively. The fiber exhibits a wide range of high laser gain. Figure 1 shows forward amplified spontaneous emission (ASE) spectra and laser spectra generated from a few-centimeters-long Tm^{3+} -doped germanate fiber pumped with laser diodes at 805 nm. Laser operation over a wide range of wavelengths, for example at 1740 and 2017 nm as shown in Fig. 1, can be easily achieved when a laser cavity is formed by two passive distributed Bragg reflectors, i.e., fiber Bragg gratings (FBGs).

A single-frequency fiber laser operating at 1893 nm was built and characterized. The laser cavity is established by two spectrally narrow FBGs at 1893 nm with an estimated bandwidth of 0.1 nm (or 8 GHz) and grating length of ~ 1 cm. The FBGs were written on commercial single-mode fibers and they were fusion-spliced to a 2 cm long piece of active fiber to form the cavity in the same way as we did for the single-frequency fiber laser at 1 and 1.55 μm (Refs. 1 and 2). Total insertion loss of the fiber laser chain including the two splicing junctions and propagation loss was measured to be 1.6 dB at 1310 nm. The output coupler with $R \sim 90\%$ was written into polarization-maintaining (PM) fiber (Nufern, PM1550), while the high-reflectivity grating ($R > 99\%$) was written into non-PM fiber (Corning, SMF-28). The active fiber is non-PM fiber; however, birefringence of the PM FBG (output coupler) splits its reflection into two peaks,² and only one of the two peaks spectrally overlaps with the reflection of the non-PM FBG. Thus, optical feedback can be realized for one polarization only, which ensures the laser oscillation in a single polarization state. Figure 2 shows output power of the laser as a function of launched pump power. The inset shows the laser spectra at 1893 nm recorded by an optical spectrum analyzer¹¹ (Agilent 86140B). The laser has a 30 mW threshold of launched pump power and a maximum output power of more than 50 mW at pump power of 190 mW. Slope efficiency of the single-frequency laser is about 35% with respect to launched pump power, which is 1 order of magnitude larger than that of those silica-

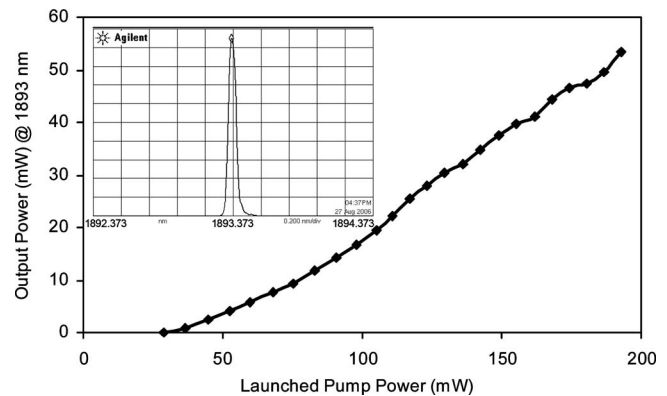


Fig. 2. Laser output power at 1893 nm as a function of launched power.

based DFB fiber lasers reported before.^{3,8} Single-frequency operation of the laser was confirmed by using an in-house scanning fiber Fabry-Perot interferometer (FFPI) with free spectral range FSR ~ 200 MHz that was constructed by a 50 cm long passive single-mode fiber with high-reflectivity dielectric coatings on both fiber ends at 1.9 μm . Figure 3 shows the FFPI scanning spectrum over one FSR of the interferometer. Although the FFPI has a much smaller FSR than the laser cavity (with FSR of 3–4 GHz), the single interference fringe generated by the FFPI over one FSR of the interferometer indicates that the laser was operating in single longitudinal mode, which is the result of competition of the very few cavity modes (2–3 modes) within the bandwidth (~ 8 GHz) of the two spectrally narrow FBGs.

With the monolithic all-fiber cavity design and our expertise in package technology as well, the fiber laser exhibits narrow linewidth and high-frequency stability. We have used a homemade Michelson fiber interferometer to measure the frequency noise of the fiber laser. Figure 4 shows the experimental setup for the frequency noise measurement. The fiber laser cavity was packed in a compact, acoustically damped package, and it was backward pumped by a single-mode laser diode at 805 nm through a fuse-based WDM for 800/1900 nm. The other end of the cavity was angle cleaved. The laser signal was fed into a Michelson interferometer. The Michelson interferom-

eter has 5 m total path mismatch of fiber with high-reflectivity dielectric coatings on both fiber ends at $1.9 \mu\text{m}$. The interference signal was detected with a fast photodiode and analyzed by a dynamic signal analyzer.

Figure 5 shows frequency noise spectra for the 1893 nm fiber laser. Reference data for our two standard fiber lasers at 1550 and 1064 nm, whose heterodyne spectral linewidth was well characterized to be 3 kHz (Refs. 1 and 2), are used for comparison. It is clear that the frequency noise of the 1893 nm laser is 10 dB higher than that of the two reference lasers, indicating that the linewidth of the 1893 nm laser is broader than 3 kHz. It is even worse at the low-frequency region. Higher frequency noise of the 1893 nm fiber laser has been mainly attributed to the fact that no FBG was used as a wavelength locker in the 805 nm laser diode for pump wavelength and intensity stabilization. In contrast, the pump lasers for the two reference fiber lasers are commercial FBG-stabilized 980 nm pump diodes. It should be noted that there might be other mechanisms for the higher frequency noise of the 1893 nm laser. For example, the cross-relaxation process, which exists in the 1893 nm laser (with heavily Tm^{3+} -doped fiber), but not in the 1550 and 1064 nm fiber lasers (with heavily Er and/or Yb-doped fiber), might bring some additional noises in the Tm^{3+} -doped fiber laser. This needs to be further investigated.

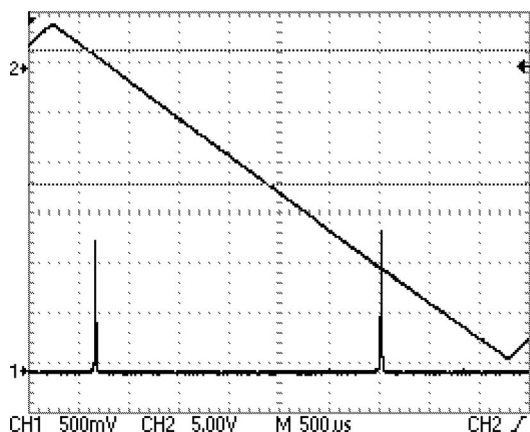


Fig. 3. Scanning spectrum over one free spectrum range of the FFPI indicating single-frequency operation of the laser.

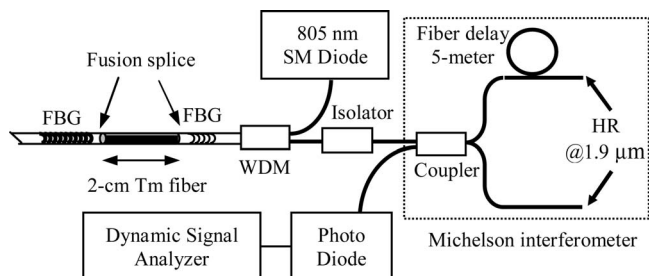


Fig. 4. Experimental setup for frequency noise measurement of the laser. HR, high reflectance; SM, single mode.

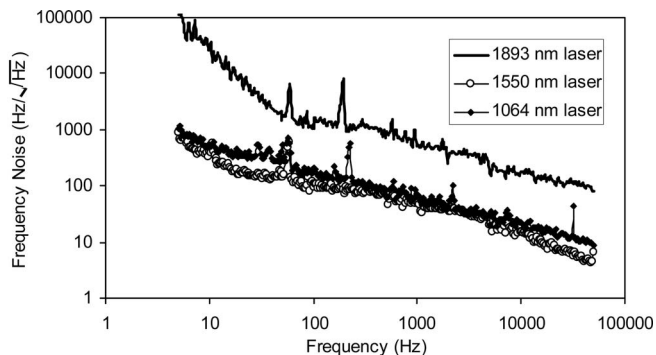


Fig. 5. Frequency noise spectra of the 1893 nm laser and two reference lasers at 1550 and 1064 nm with 3 kHz linewidth.

In conclusion, we use a short piece of heavily Tm^{3+} -doped germanate fiber pumped by laser diodes at 805 nm to demonstrate efficient cw laser operation in a wide range of wavelengths from 1740 to 2017 nm. Efficient diode-pump single-frequency fiber laser operation was demonstrated, for the first time to our knowledge, with 30 mW threshold pump power and 35% slope efficiency for a specific laser at 1893 nm. Frequency noise of the fiber laser at 1893 nm has been measured, indicating 10 dB more noise than that of our standard 3 kHz fiber lasers at 1550 and 1064 nm. J. Geng's e-mail address is geng@npphotonics.com.

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