

Efficient Single-Frequency Thulium Doped Fiber Laser Near 2- μm

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Abstract: We demonstrate highly efficient diode-pumped single-frequency fiber laser with 35% slope efficiency and 50mW output power operating near 2 μm , which generated from a 2-cm long piece of highly Tm^{3+} -doped germanate glass fiber pumped at 800nm.

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1. Introduction

Coherent laser sources with single-frequency narrow-linewidth output are required for many applications. Diode-pumped single-frequency solid-state lasers (e.g., monolithic non-planar Nd:YAG ring oscillator laser or NPRO laser) have been the well-known low-noise coherent laser sources with a spectral linewidth ranging from hundreds kHz to as narrow as a few kHz 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 they also offer multiple wavelength regions at 1 μm , 1.5 μm , and 2 μm [1-3], and many unique advantages over conventional solid-state lasers in terms of reliability, ruggedness, and compactness. The wide ranges of operating wavelength 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 μm based on Tm^{3+} ions has attracted intense interest for two decades for their wide applications in medicine, LIDAR, and materials processing [4-6]. Due to the so-called cross-relaxation process, efficient 2- μm laser operation (on the ${}^3\text{H}_4 - {}^3\text{H}_6$ transition) has been achieved in Tm^{3+} -doped crystals by using the ${}^3\text{F}_4 - {}^3\text{H}_6$ pump transition of Tm^{3+} near 800nm. The Tm^{3+} cross-relaxation is a non-radiative process in which a single excited Tm^{3+} ion in the ${}^3\text{H}_4$ level generates two Tm^{3+} ions in the ${}^3\text{F}_4$ upper laser level, potentially yielding 200% quantum efficiency for 2- μm laser operation [4]. 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 (<2wt%) but it approaches unity (200% quantum efficiency) at high concentration (~5wt%) that make the laser extremely efficient.

The same laser action can be achieved in Tm^{3+} -doped fibers [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- μm laser transition because of the high phonon energy (1100 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 790nm showed that it is less efficient (1mW maximum output at 1735nm and 0.2% slope efficiency) [3]. Another silica-based DFB fiber laser recently also reported a poor efficiency (5mW maximum output at 1836nm and 1% slope efficiency) that was in-band pumped at 1565nm [8]. Recently, however, we achieved a highly efficient 1.9- μm 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 cm^{-1}) in the heavily doped germanate glass. In this paper, we report the first diode-pumped single-frequency fiber laser operation near 2- μm [10], whose efficiency is much higher than those silica-based Tm^{3+} -doped fiber lasers by using the heavily Tm^{3+} -doped germanate fiber. Frequency noise of a diode-pumped single-frequency fiber laser at 1893nm has been measured and compared with the data for our standard single-frequency fiber lasers with 3kHz heterodyne linewidth at 1550 and 1064nm.

2. Wide Range of Laser Operation

The single-mode germanate glass fiber with 5-wt% Tm_2O_3 doping concentration that was fabricated in house was used in the experiment. Numerical aperture (NA) of the fiber is 0.15, while core diameter and outer diameter of the fiber are $7\mu\text{m}$ and $125\mu\text{m}$, respectively. The fiber exhibits wide range of high laser gain. Figure 1 shows forward amplified spontaneous emission (ASE) spectra and laser spectra generated from a few centimeter-long Tm^{3+} -doped germanate fiber when pumped with laser diodes at 805nm. Laser operation at wide range of wavelength, for example at 1740nm and 2017nm as shown in Figure 1, can be easily achieved when a laser cavity is formed by two spectrally narrow passive distributed feedback reflective (DBR) mirror, i.e., fiber Bragg gratings (FBG). The FBGs were written on the standard telecom single-mode fiber (Corning SMF-28) and they were fusion-spliced with a short piece of active fiber to form the cavity.

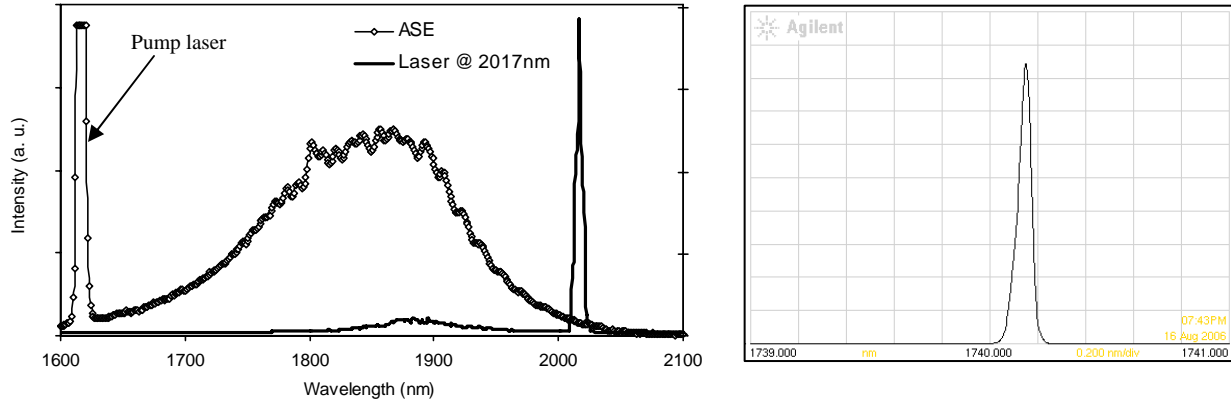


Fig. 1. Left graph shows forward ASE spectra (and pump laser with open circle) and laser spectra at 2017nm (solid line) recorded by using a monochromator and a cooled InAs detector. Right graph shows the laser spectra at 1740nm recorded by an optical spectrum analyzer (Agilent 86140B).

3. Performance of Single-Frequency Fiber Laser at 1893nm

A single-frequency fiber laser operating at 1893nm was built. The laser cavity is established by two fiber Bragg gratings (FBG). The FBGs are fusion spliced to a 2-cm long piece of active fiber in the same way as we did for our standard single-frequency fiber lasers at 1- μm and 1.55- μm . Figure 2 shows output power of the laser as a function of launched pump power. The inset shows the laser spectra at 1893nm recorded by an optical spectrum analyzer (Agilent 86140B). The laser has a 30-mW threshold of launched pump power and a maximum output power of more than 50mW at pump power of 190mW. Slope efficiency of the single-frequency laser is about 35%, which is one order of magnitude larger than that of those silica-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 FSR~200MHz 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 free spectral range, indicating single frequency operation of the laser.

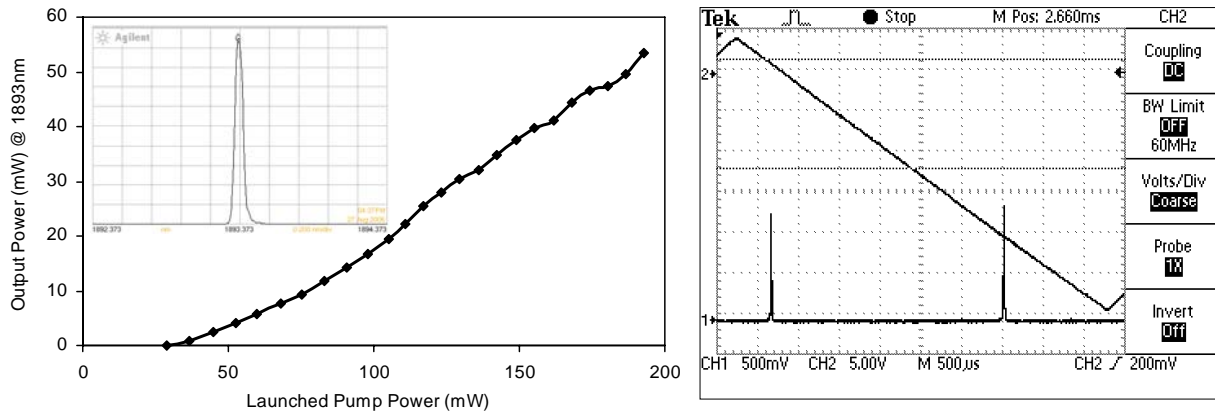


Fig. 2. Laser output power at 1893nm as a function of launched power.

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

With a monolithic all-fiber cavity design and our expertise 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 805nm through a fuse-based WDM for 800/1900nm. The other end of the cavity was angle-cleaved. The laser signal was fed into a Michelson interferometer. The Michelson interferometer has 5-m total path mismatch of fiber with high-reflectivity dielectric coatings on both fiber ends at 1.9- μm . The interference signal was detected with a fast photodiode and analyzed by a dynamic spectrum analyzer (DSA).

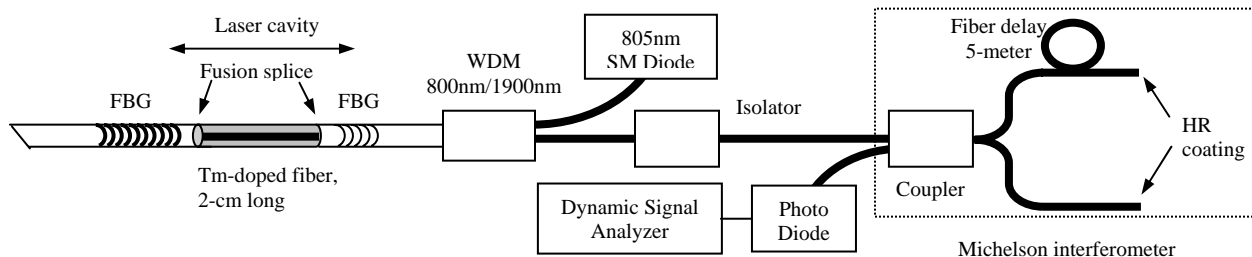


Fig. 4. Experimental setup for frequency noise measurement of the laser.

Figure 5 shows frequency noise spectra for the 1893-nm fiber laser. Reference data for our two standard fiber lasers at 1550nm and 1064nm, whose heterodyne spectral linewidth was well characterized to be 3kHz [1,2], are used for comparison. It is clear that the frequency noise of the 1893nm laser is 10-dB higher than that of the two reference lasers, indicating that the linewidth of the 1893nm laser is broader than 3kHz. It is even worse at low frequency region. Higher frequency noise of the 1893nm fiber laser has been 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.

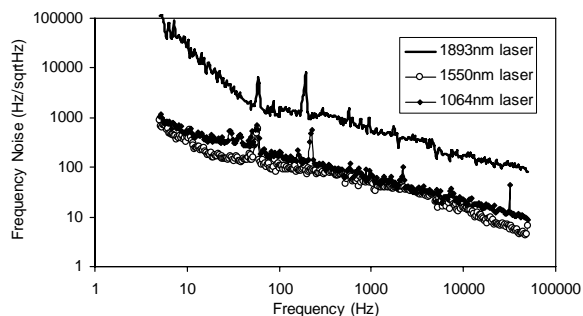


Fig. 5. Frequency noise spectra of the 1893-nm laser and two reference lasers at 1550nm and 1064nm with 3kHz linewidth.

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

4. Reference

1. Y. Kaneda, Ch. Spiegelberg, J. Geng, Y. Hu, T. Luo, J. Wang, and S. Jiang, "200-mW, narrow-linewidth 1064.2 nm Yb-doped fiber laser", in Proceedings of the Conference on Lasers and Electro-Optics (Optical Society of America, Washington, D.C., 2004), paper CThO3.
2. Ch. Spiegelberg, J. Geng, Y. Hu, Y. Kaneda, S. Jiang, and N. Peyghambarian, "Low noise narrow linewidth fiber laser at 1550 nm", *J. Lightwave Technol.* **22**, 57-62 (2004).
3. S. Agger, J. H. Povlsen, P. Varming, "Single-frequency thulium-doped distributed feedback fiber laser", *Opt. Lett.* **29**, 1503-1505 (2004).
4. L. Esterowitz, "Diode-pumped holmium, thulium, and erbium lasers between 2 μm and 3 μm operating CW at room-temperature" *Optical Engineering* **29**, 676-680 (1990).
5. R.C. Stoneman, L. Esterowitz, "Efficient, broadly tunable, laser-pumped Tm-YAG and Tm-YSGG CW Lasers" *Optics Letters* **15**, 486-488 (1990).
6. S.W. Henderson, P.J.M. Suni, C.P. Hale, S.M. Hannon, J.R. Magee, D.L. Bruns, and E.H. Yuen, "Coherent laser-radar at 2 μm using solid-state lasers" *IEEE Transactions on Geoscience and Remote Sensing*, **31**, 4-15 (1993).
7. R.A. Hayward, W.A. Clarkson, P.W. Turner, J. Nilsson, A.B. Grudin, D.C. Hanna, "Efficient cladding-pumped Tm-doped silica fibre laser with high power single mode output at 2 μm ", *Electronics Letters*, **36**, 711-712 (2000).
8. N. Y. Voo, J. K. Sahu, and M. Ibsen, "345-mW 1836-nm single-frequency DFB fiber laser MOPA," *IEEE Photonics Technology Letters*, **17**, 2550-2552 (2005).
9. J. Wu, S. Jiang, T. Luo, J. Geng, N. Peyghambarian, and Norman P. Barnes, "Efficient Thulium-doped 2- μm germanate fiber laser," *IEEE Photonics Technology Letters*, **18**, 234-236 (2006).
10. S. Jiang, C. Spiegelberg, T. Luo, "Single-frequency narrow linewidth 2- μm fiber laser," US patent No. 7106762.