Single-frequency narrow-linewidth Tm-doped fiber laser using silicate glass fiber

Jihong Geng,[1,*] Qing Wang,[1] Tao Luo,[1] Shibin Jiang,[1] and Farzin Amzajerdian[2]

[1]*AdValue Photonics, 4585 S Palo Verde Road, Suite 405, Tucson, Arizona 85714, USA*
[2]*NASA Langley Research Center, 5 North Dryden Street, Hampton, Virginia 23681, USA*
Corresponding author: jgeng@advaluephotonics.com

Received August 19, 2009; revised September 23, 2009; accepted October 13, 2009;
posted October 15, 2009 (Doc. ID 115924); published November 9, 2009

Single-frequency laser operation near 2 μm has been demonstrated in an all-fiber short-cavity (2–6 cm) distributed feedback laser cavity using both cladding- and core-pump configurations in a newly developed heavily Tm-doped multicomponent silicate glass fiber. Using a single-mode Er-doped fiber laser at 1575 nm as a core-pump source, a 2-cm-long distributed Bragg reflector fiber laser delivers single-frequency output at 1950 nm with laser linewidth less than 3 kHz, which is, to the best of our knowledge, the narrowest linewidth demonstrated to date from any 2 μm single-frequency laser. © 2009 Optical Society of America

OCIS codes: 060.2320, 140.3070, 140.3510, 140.3570.

Single-frequency fiber lasers at 1 and 1.55 μm have been well developed and commercialized with a typical design of a very short laser cavity in combination with narrowband fiber Bragg gratings for robust single-frequency operation. Similar laser development near 2 μm has received intense interest in recent years. To date, two different kinds of Tm-doped glass fibers have been used for single-frequency laser operation near 2 μm. They are silica glass fiber with a distributed feedback (DFB) cavity configuration [1–4] and germanate glass fiber with a distributed Bragg reflector (DBR) configuration [5]. Previous experiments have indicated that Tm-doped silica fibers offer very low efficiency (0.3%–1%) for single-frequency laser operation [1,2]. The low efficiency can be attributed to the low pump absorption within a short piece of active fiber used in single-frequency Tm-doped silica fiber DFB lasers. Recently, dramatic improvements in Tm-doped silica fiber technology (by codoping some other ions such as Ge^{4+} and Al^{3+} in silica glass of the fiber core during the the chemical vapor deposition process) have led to very high laser efficiency ($>54\%$) in high-power Tm-doped fiber laser–amplifier experiments [6,7]. Significantly improved laser efficiencies (10%–27%) have also been reported in single-frequency silica fiber lasers [3,4], which is close to $\sim 35\%$ for a germanate glass fiber laser [5].

In this Letter, we report a glass fiber, i.e., heavily Tm-doped multicomponent silicate glass fiber, for efficient single-frequency laser operation near 2 μm. The glass host was fabricated in house by mixing and melting chemical compounds together to form the multicomponent glass, instead of the chemical vapor deposition process used for doped silica fibers. Because of the less-defined glass network, the multicomponent glass permits a high doping concentration of rare-earth ions (Tm^{3+}), which in turn permits high pump absorption over a relatively short active fiber length and allows taking advantage of a 2-for-1 cross-relaxation process in the heavily doped Tm^{3+} system. The main glass network that forms our glass host is SiO_2, the same material as standard silica glass fiber. Therefore, this fiber provides much stronger mechanical strength and better compatibility with silica fiber than germanate glass fiber, yielding more robust fusion splicing between the active fiber and standard passive silica fiber needed for fiber Bragg gratings (FBGs). With the newly developed Tm-doped silicate glass fiber, efficient single-frequency laser operation has been demonstrated in a short-cavity DBR fiber laser in both cladding- and core-pump configurations. Less than 3 kHz linewidth has been demonstrated in a core-pumped Tm-doped DBR fiber laser, which is, to the best of our knowledge, the narrowest linewidth demonstrated to date from 2 μm single-frequency fiber lasers.

For this experiment, a single-mode Tm-doped double-cladding silicate fiber was designed so that it can be used for both the cladding pump and the core pump. A rod-in-tube fiber drawing technique was used to fabricate the fiber in house. The fiber core has a diameter of 10 μm and NA of 0.136 with a Tm-doping concentration of 5% by weight. The high doping concentration of the fiber enables efficient cross relaxation, as demonstrated in crystalline hosts and other glass hosts. The mode field diameter of the fiber core is nearly matched with that of commercial single-mode fiber at the wavelength of 2 μm. Its inner cladding is 125 μm in diameter, which is also matched with both commercial single-mode FBG fiber and commercial pump combiner with a double-cladding fiber (125/250 μm diameter, 0.46 NA). The inner cladding of the active fiber is surrounded by a 165 μm diameter outer cladding glass with NA $=0.58$ to confine the multimode pump laser within the 125 μm region. The use of glass cladding in the silicate double-cladding fiber allows potentially for much higher power handling capability than those standard polymer-based double-cladding silica fibers. A low-index silicate rod was inserted into the inner cladding for the enhancement of cladding pump absorption (>12 dB/m near 800 nm).

DBR fiber lasers were built with a short piece of active fiber and a pair of FBGs at 1950 nm written in commercial single-mode fibers. The lasers were cladding pumped by several multimode diodes at 793 nm via a fiber pump combiner. Figure 1 shows the laser

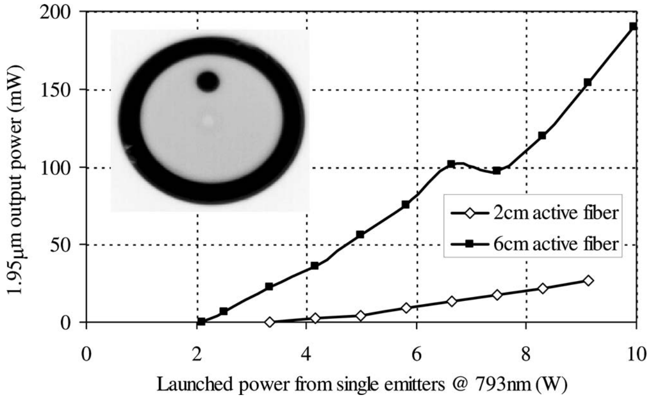

Fig. 1. 1950 nm laser output versus launched multimode pump power at 793 nm in a cladding-pumped short-cavity DBR fiber laser. Inset, microscopic image of the active fiber.

output power as a function of launching pump power. With 2-cm and 6-cm-long active fiber, the DBR fiber lasers have a laser threshold at 3.2 W and 2 W of pump power, respectively. This is the first demonstration of an all-fiber cladding-pumped DBR laser using such a short piece of active fiber. For 6-cm-long DBR fiber laser, the output power variation at 7 W of pump power was due to mode-hopping from one longitudinal mode to another in the DBR fiber laser. Higher pump power was available from pump emitters, but the DBR laser could not survive for long-term operation at pump powers greater than 10 W, as the high-reflective FBG strongly scatters the pump laser radiation, damaging the low-index coating around the FBG. Nevertheless, the demonstration of high pump absorption and high gain per unit length in the cladding-pump configuration indicates that our active fiber can be used in applications that require high gain and high power from a short piece of active fiber.

The 2 cm DBR fiber laser was also core pumped with a fiber master oscillator power amplifier system operating at 1575 nm. The master oscillator was a 45 mW single-mode diode-pumped Er fiber laser, and its power was boosted by a cladding-pumped Er/Yb codoped fiber amplifier delivering maximum output power of 600 mW at 1575 nm. No attempt was made to spectrally filter broadband spontaneous emission, which counts for ~5% of the total power. Core pump absorption of our Tm-doped fiber was measured to be about 1.7 dB/cm at 1575 nm. Therefore, almost 55% of the launched pump power was absorbed by the 2-cm-long active fiber. Figure 2 shows the laser output power as a function of launching pump power, and the laser spectrum after filtering the pump beam. The slope efficiency of the laser was measured to be 20.4% with respect to the launching pump power and greater than 37% relative to the absorbed pump power. The relatively high laser threshold is attributed to high cavity loss, including output coupling loss (~70% reflectivity) and splicing losses (~2.2 dB) between the active fiber and two FBGs. After optimizing the reflectivity of the output coupler and the process for fiber fusion splicing, further improvement in the laser efficiency can be expected.

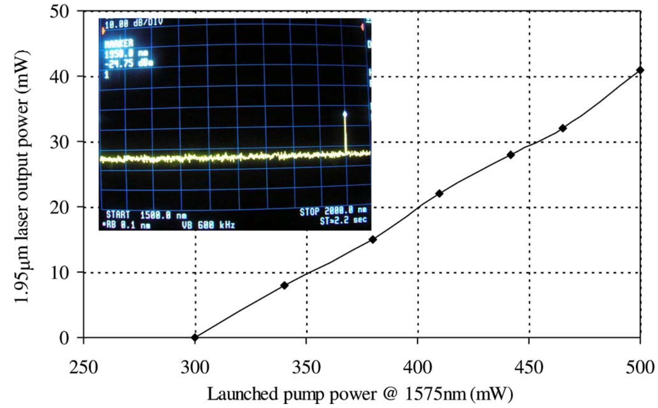

Fig. 2. (Color online) 1950 nm laser output versus launched single-mode pump power at 1575 nm in a core-pumped short-cavity DBR fiber laser. Inset, spectrum of the DBR fiber laser.

Single-frequency operation of the laser was confirmed by using a homemade fiber-based scanning Fabry–Perot interferometer with free spectral range (FSR) of about 800 MHz built from a 12 cm long piece of passive single-mode fiber with high-reflective dielectric coatings on both fiber ends near the 2 μm wavelength. The interferometer was scanned by applying a sawtooth voltage over a small piece of piezo actuator, on which a portion of the fiber of the interferometer was glued. Figure 3 shows the laser spectrum over an FSR.

The intensity noise peak of the DBR laser was characterized. Figure 4 shows oscilloscope traces for the DBR fiber laser intensity and its fast Fourier transform (FFT) spectrum. Two relaxation oscillation peaks appear in the spectra. Experiments show that the high-frequency noise peak is dependent only on the total pump power, while the low-frequency noise peak was varied only with the output power of the Er-doped fiber oscillator. This indicates that the high-frequency peak is due to the relaxation oscillation of the Tm-doped DBR laser cavity, while the low-frequency noise peak is a noise transferred from the pump source to the Tm-doped laser. A similar observation has been reported by others in a Tm-doped DFB fiber system but with a different assignment for the two noise peaks [3].

The DBR laser exhibits a very narrow linewidth or low frequency noise. A Michelson fiber interferometer

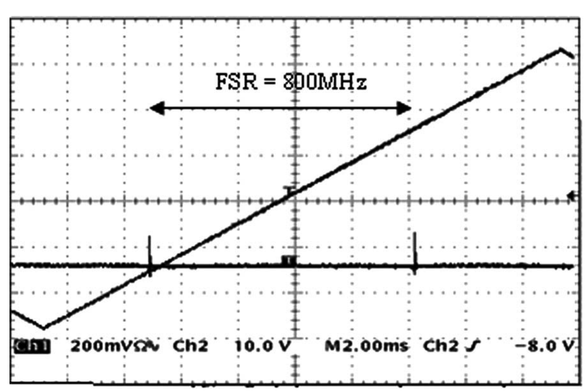

Fig. 3. Scanning spectrum of the fiber Fabry–Perot inteferometer.

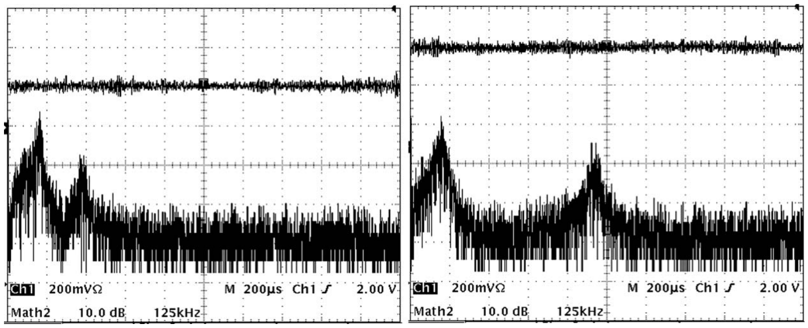

Fig. 4. Intensity of the DBR fiber laser and its FFT spectrum at two different pump powers. Left, 340 mW pump power; right, 550 mW pump power.

was used to characterize the laser frequency noise with unbalanced fiber length of 25 m. Figure 5 shows the measured laser frequency noise, which was obtained by analyzing the interferometric signal with a dynamic signal analyzer. The noise floor of the test setup and the published reference data [5,8] for a 3 and a 30 kHz linewidth laser are also plotted in the figure for comparison. It is clear that the frequency noise of this DBR fiber laser is even lower than that of commercial 3 kHz linewidth lasers, especially in the frequency range of 100 Hz to 40 kHz. The relatively high-level noises at the low-frequency side (<100 Hz) can be attributed to thermal fluctuations in the experimental setup, and the high-frequency (>40 kHz) noises are generated by the pump intensity noise described earlier (Fig. 4). Both of these noise sources can be minimized or eliminated with an improve laser design. This suggests that the linewidth of this DBR fiber laser is close to or even narrower than 3 kHz, 1 order of magnitude improved from that reported previously [3,5]. The narrow linewidth of the DBR fiber laser can be attributed to low noise in its pump laser, i.e., the single-mode Er-doped fiber laser, as compared with the unstabilized single-mode 800 nm laser diode used in [5]. The low frequency noise or the narrow spectral linewidth of a single-frequency 2 μm fiber laser is essential to its applications in mid-IR precise frequency comb metrology.

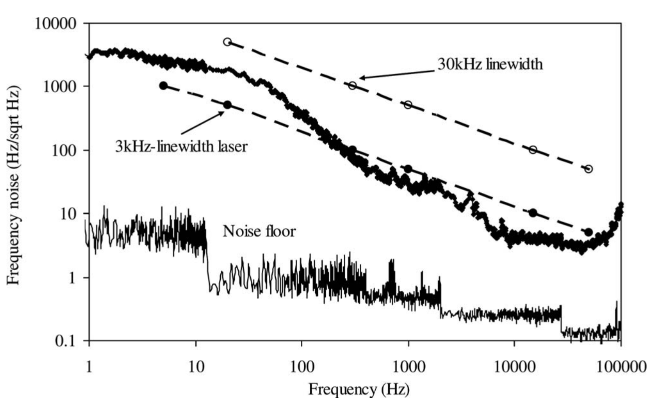

Fig. 5. Frequency noise spectrum of the DBR fiber laser, as compared with noise floor and the published data [5].

In summary, a glass host for heavily Tm-doped fiber, i.e., multicomponent silicate glass fiber, has been demonstrated for single-frequency laser operation near the 2 μm wavelength region. Both cladding- and core-pump configurations have been used to pump short-cavity DBR fiber lasers at 1950 nm, indicating high gain per unit length of the doped fiber in both pump configurations. The intensity noise and the frequency noise of the core-pumped single-frequency DBR fiber laser has been characterized. The frequency noise measurement of the 1950 nm fiber laser suggests that the laser linewidth is less than 3 kHz.

This work was supported mainly by NASA SBIR project NNX09CF21P. The authors acknowledge the technical support of Dr. Pamela Chu from NIST under contract SB1341-09-SE-0621. This work was also supported by the Air Force Research Laboratory, Materials and Manufacturing Directorate, Wright-Patterson AFB, under contract FA8650-08-C-5401. The authors also acknowledge Dr. Jonathan Goldstein from the Air Force Research Laboratory, Materials and Manufacturing Directorate, Wright-Patterson AFB, for his technical support.

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