Mode-locked 2 μm laser with highly thulium-doped silicate fiber

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We report self-starting passively mode-locked fiber lasers with a saturable absorber mirror using a piece of 30-cm-long newly developed highly thulium (Tm)-doped silicate glass fibers. The mode-locked pulses operate at 1980 nm with duration of 1.5 ps and energy of 0.76 nJ. This newly developed Tm-doped silicate fiber exhibits a slope efficiency of 68.3%, an amplified spontaneous emission spectrum bandwidth (FWHM) of 92 nm, and a gain per unit length of greater than 2 dB/cm. To the best of our knowledge, it is the first demonstration of mode-locked 2 μm fiber laser using shorter than 1-m-long active fiber, which paves the way for the demonstration of mode-locked fiber laser at 2 μm with gigahertz fundamental repetition rate. © 2009 Optical Society of America

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Mode-locked fiber lasers at 1 and 1.5 μm wavelength range have been studied extensively in recent decades. Ultrashort pulse diode-pumped fiber lasers have been used for many scientific and industrial applications. Recently thulium (Tm)-doped fiber lasers attract significant attention because Tm-doped fibers have a wide gain spectrum from 1.8 to 2.1 μm [1–3] and have been demonstrated as high-power and highly efficient light sources near 2 μm [4–6]. 2 μm fiber lasers are useful for a variety of attractive applications including eye-safe lidar, medicine, spectroscopy, remote sensing, and generation of mid-IR light source. Thulium fiber laser exhibits a broad laser wavelength tuning range, implying that Tm-doped fiber lasers could generate ultrashort pulses. There are several demonstrations of passively mode-locked Tm-doped fiber lasers, and mode-locking mechanisms include additive-pulse mode locking [7,8], semiconductor saturable absorber mirrors (SESAMs) [9,10], and carbon nanotube based saturable absorbers [11,12]. For additive-pulse mode locking, bulk optics components inside the laser cavity cause the complexity and make fiber lasers lose their essential benefit of compactness. Although single-wall carbon nanotubes have shown ultrafast saturable absorption, their long-term stability needs to be further evaluated. So using SESAMs for mode locking of Tm-doped fiber lasers remains a good approach.

Tm-doped or Tm–Ho-codoped silica fibers have been used for the reported demonstrations of mode-locked fiber lasers near 2 μm. Because of the limited Tm doping concentration in silica fiber, typically several meters of Tm-doped silica fiber are needed to build a mode-locked silica fiber laser. As a result, the fundamental repetition rate of the mode-locked silica fiber laser is limited to far below the gigahertz repetition rate, which is desirable for many important applications, such as frequency comb metrology. Meanwhile the quantum efficiency of Tm-doped silica fiber lasers at 2 μm is limited owing to the relatively low Tm^{3+} doping concentration in silica fiber. Multicomponent silicate glass can be an ideal host for highly Tm-doped fiber laser at 2 μm, since Tm^{3+} can be highly doped into silicate glass, resulting in the so-called cross-relaxation energy transfer and greatly improving the quantum efficiency. Importantly, with the high Tm^{3+} doping concentration, both the pump absorption efficiency and the gain per unit length of the Tm-doped silicate fiber increase accordingly, which allows an efficient laser operation in a short piece of doped active fiber. Recently we have developed a highly Tm-doped silicate glass fiber with a high efficiency and a high gain per unit length. In this Letter we have demonstrated a mode-locked 2 μm fiber laser with SESAMs using a piece of 30 cm newly developed Tm-doped silicate glass fiber. This preliminary experimental demonstration indicates that mode-locked 2 μm fiber laser with a gigahertz fundamental repetition rate is achievable in a highly Tm-doped silicate fiber.

Tm-doped silicate glasses, undoped cladding glasses, and fiber preforms were designed and fabricated in house. The Tm^{3+}-doping concentration is 5 wt. %. Rod-in-tube technique was used to fabricate single-mode double glass-cladding fibers. Fiber drawing was carried out on our in-house fiber drawing tower. Two double-cladding Tm-doped fibers were fabricated for this demonstration. Both fibers have an inner cladding diameter of 125 μm, an outer cladding diameter of 160 μm, and an inner cladding NA of 0.58. The outer cladding is a glass cladding. One double-cladding Tm-doped fiber has a core diameter of 18 μm and an NA of 0.07, which was used for fiber laser efficiency characterization. A relatively large core diameter is designed to efficiently absorb the pump power. The other fiber has a core diameter of 10 μm and an NA of 0.136 to match the mode-field diameter of the SMF-28 fiber at 2 μm, which is used for mode-locking fiber laser experiments. The inner cladding has the diameter of 125 μm and an NA of 0.58 to efficiently couple pump light from the pump combiner output fiber (125 μm, 0.46 NA).

Figure 1 illustrates the laser output power versus the absorbed pump power of the 18 μm core diameter fiber pumped with a 798 nm diode laser. The

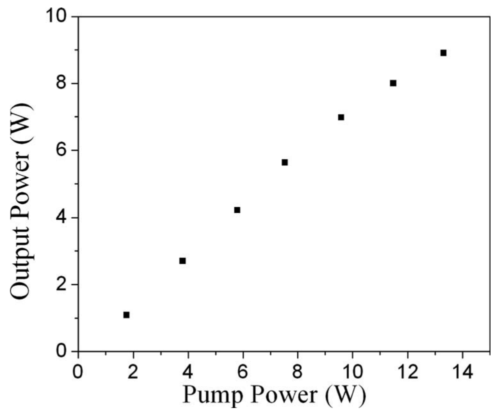

Fig. 1. Laser output power versus the absorbed pump power of the 20-cm-long Tm-doped silicate fiber (with a core diameter of 18 μm) laser.

Tm-doped fiber is 20 cm long. Dielectric coating at the end of the pump delivery fiber was used as the high reflector. Fresnel reflection at the end of the Tm-doped silicate glass fiber (~4%) was used as the output coupler. A high slope efficiency of 68.3% was achieved.

Figure 2 shows the measured amplified spontaneous emission (ASE) spectrum of 10 μm core diameter fiber. The length of the Tm-doped silicate fiber is longer than 5 m, and both ends of the fiber were angle cleaved to eliminate backreflection. The ASE output exhibits a FWHM bandwidth of ~92 nm and an average power of 80 mW. By using the identical experimental setup the ASE output from the Tm-doped silica fiber has a FWHM bandwidth of ~45 nm, which is less than half of the Tm-doped silicate fiber. The microscope image of the fiber cross section is shown in the inset of Fig. 2. The pump absorption at 798 nm was measured to be 12 dB/m. The solid rod inserted into the inner cladding helps to improve the pump absorption by 1–2 dB/m when longer fiber is used. In a separate experiment [13] we demonstrated single frequency fiber laser using a piece of 2-cm-long fiber and confirmed a gain per unit length of greater than 2 dB/cm. The high slope efficiency, the broad gain bandwidth, and the high gain per unit length of this newly developed fiber make the Tm-doped silicate fiber an excellent candidate for building a fiber-based high-repetition-rate femtosecond frequency comb near 2 μm.

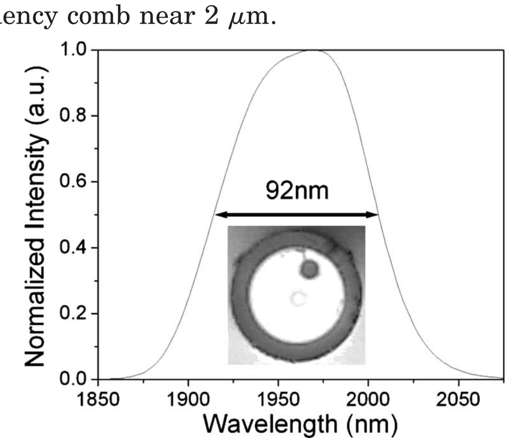

Fig. 2. ASE spectrum of Tm-doped silicate glass fiber. Inset, microscope image of the fiber cross section.

The mode-locked Tm-doped silicate fiber laser experimental setup is shown in Fig. 3. The key element used to start and maintain mode-locking operation of the laser was a resonant Sb-based saturable absorber mirror. The laser has a linear cavity, formed by a SESAM, a pump combiner, a piece of 30-cm-long double-cladding Tm-doped silicate fiber with 10 μm core diameter, and a fiber loop mirror. A multimode pump combiner was used to deliver pump light to the Tm-doped fiber from a 798 nm laser diode with 0.22 NA 105 μm/125 μm fiber pigtail. The fiber loop mirror, fabricated with a 50/50 fiber coupler, has an estimated reflectivity of ~90% at 2 μm, and its length is ~1 m. Owing to the large difference in the refractive index between passive silica fibers (commercial single-mode silica fibers) and the Tm-doped silicate fiber, we angle cleave and fusion splice the two different kinds of fibers to prevent any spurious reflection that could be detrimental to mode-locking operation. The fiber output end was also angle cleaved to eliminate backreflection. Each angle-cleaved splicing has an estimated loss of ~1.5 dB. Low-index recoating was carried out at the splicing joint section between the combiner output fiber and the Tm-doped silicate fiber to couple the pump light efficiently. The input end of the pump combiner signal fiber was directly butt coupled to the saturable absorber mirror.

When the pump power was increased, the fiber laser operation went through several working regimes. First, the cw laser operation was obtained after the laser threshold (~2.1 W) was reached. This relatively high laser threshold was due to the large loss of two angle-cleaved fusion-splicing joints. Then Q-switching or Q-switched mode locking could be observed. When the pump power was increased to higher than 2.2 W, the cw mode locking was achieved. A typical oscilloscope trace of the mode-locked pulse train is shown in the inset of Fig. 4. The repetition rate of the pulse train is ~13.2 MHz. The relatively long cavity is owing to the uncut passive fibers and long fiber in the loop mirror. When the pump power was further increased, the output average power of the CW mode locking increased as well. Once the average output power was larger than 10 mW, the laser could not operate in the regime of single pulse per round trip and the previous single pulses started to split into two or three pulses, which results from the upper limit of the soliton fiber laser pulse energy. This limit is determined by laser cavity parameters, including saturable absorber's saturation energy, modulation depth, cavity dispersion, and self-phase-modulation. Beyond this pulse energy limit, multiple pulses with reduced energy and longer duration are favored over a single short pulse in terms of mode-locking stability. For the maximum output average

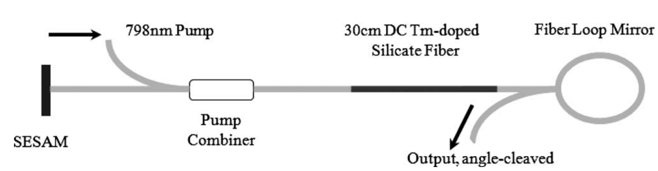

Fig. 3. Schematic of mode-locked Tm-doped silicate fiber laser.

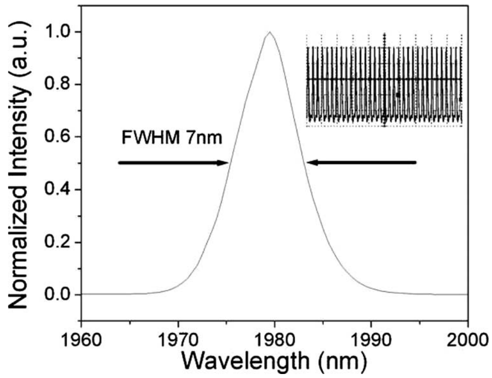

Fig. 4. Laser spectrum of mode-locked Tm-doped silicate fiber laser. Inset, pulse train of the mode-locked laser.

power of 10 mW in single-pulse regime, the pulse energy is around 0.76 nJ.

A typical mode-locked laser spectrum is presented in Fig. 4. The central lasing wavelength is around 1980 nm, which corresponds to the resonant peak of the SESAM. The FWHM is $\sim$7 nm. Considering the intrinsic large gain bandwidth of Tm^{3+}, as shown by the broad ASE spectrum of the Tm-doped silicate fiber in Fig. 2, a much broader bandwidth can be expected if a nonresonant SESAM is used. The pulse width was characterized with a commercial autocorrelator (Femtochrome Research Inc.). The intensity autocorrelation of pulses at 10 mW output is shown in Fig. 5. The FWHM of the autocorrelation trace is $\sim$2.65 ps and, for a soliton pulse, it corresponds to the pulse width of 1.5 ps. The large time–bandwidth product of 0.8 indicates a large amount of dispersion in laser pulses. Much shorter pulses could be achieved by reducing the length of the passive silica fiber inside the laser cavity. To the best of our knowledge it is the first demonstration of mode-locked fiber laser using highly Tm-doped silicate glass fiber. We plan to shorten the total cavity length to less than 10 cm by using single-mode core pumping and broadband dielectric coating as the output coupler to increase the pulse train fundamental repetition rate to approximately gigahertz.

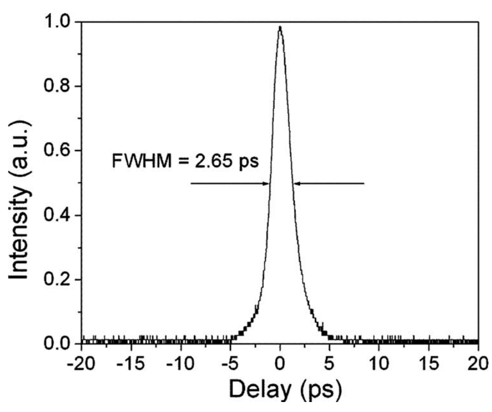

Fig. 5. Intensity autocorrelation of mode-locked Tm-doped silicate fiber laser at 10 mW output.

We have demonstrated passively mode-locked fiber laser using our newly developed Tm-doped silicate fiber. The mode-locking operation was demonstrated by using a piece of 30-cm-long active fiber, which delivers 1.5 ps laser pulses with pulse energy of 0.76 nJ. It can be expected to achieve a few hundred femtoseconds with a smaller total anomalous group-velocity dispersion by decreasing the length of the passive fiber inside the cavity. The high gain per unit length and the broad gain spectrum of the Tm-doped silicate fiber will enable us to build a femtosecond fiber frequency comb at very high repetition rates (gigahertz) at 2 μm, which is useful for frequency metrology in mid-IR wavelength range.

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