Mode-Locked Tm–Ho-Codoped Fiber Laser at 2.06 μm

Qing Wang, Jihong Geng, Zhuo Jiang, Tao Luo, and Shibin Jiang

***Abstract*—A mode-locked Tm–Ho-codoped fiber laser is reported, which is the first demonstration of a mode-locked fiber laser oscillator at the wavelength beyond 2 μm. The laser was built with a piece of newly developed Tm–Ho-codoped dc silicate fiber and a Sb-based semiconductor saturable absorber mirror (SESAM). When cladding pumped with a laser diode at 0.8 μm, the fiber laser generates mode-locked solitons at 2.06 μm with a pulse energy of 0.41 nJ and pulse duration of 1.1 ps.**

***Index Terms*—Midinfrared, mode-locking, saturable absorber.**

I. Introduction

In recent years, thulium (Tm)-doped fiber lasers have attracted significant attention because Tm-doped fibers exhibit excellent power scalability and high efficiency in a wide spectrum of laser gain between 1.8–2.0 μm. Light sources around 2 μm are useful for a variety of applications including eye-safe LIDAR, medicine, spectroscopy, remote sensing and mid-infrared (IR) generation. To further extend the wavelength beyond 2 μm from a laser oscillator, the transition between $^5I_7$ and $^5I_8$ of holmium (Ho) ions is a good choice [1]. CW high power (83 W) cladding-pumped Tm–Ho-codoped silica fiber laser has already been demonstrated with high slope efficiency [2]. For some nonlinear applications, such as optical parametrical oscillators (OPOs) or supercontinuum for mid-IR generation, high energy and high peak power pulsed holmium lasers are very desirable. In past several years, a few mod-locked Tm-doped fiber lasers have been reported [3]–[7]. However, almost all of the reported Ho-based pulsed lasers are bulky crystal lasers in the operation of Q-switching [8], active mode-locking [9] and passive mode-locking [10]. There have been very few reports on a pulsed Ho-doped fiber laser so far. Recently, a gain-switched Ho-doped fiber laser was reported [11], generating 150 ns pulses with an energy of 3.2 μJ at 2.1 μm. In addition, two soliton fiber lasers [12], [13] using Tm–Ho-codoped silica fiber were also reported recently. However, the operation wavelength of both soliton fiber oscillators were around 1.8–2 μm, which indicates that $^3F_4$ to $^3H_6$ transition of thulium ions should be responsible for the laser emission and holmium ions were not really involved in both lasers. This could be attributed to the low concentration of holmium ions in those silica glass fibers and unfavorable energy transfer between thulium ions and holmium ions, resulting in low gain at the wavelength beyond 2 μm (holmium ion emission). Also, in both demonstrations the authors used a 1.5 μm laser to core-pump ~1-meter long Tm–Ho-fiber. Based on our experimental observations, this pump configuration facilitates lasing at short wavelengths. For example, the ASE center wavelength for the same Tm silica fiber is 1880 nm with core-pump and 1950 nm with clad-pump. In this letter, we report a mode-locked fiber laser at a wavelength beyond 2 μm based on a newly developed Tm–Ho-codoped silicate fiber. Passively mode-locked pulses with the pulse energy of 0.41 nJ and the duration of 1.1 ps at 2.06 μm were delivered from this laser. To our best knowledge, this is the first demonstration of mode-locked fiber laser oscillator at this wavelength range.

In heavily Tm-doped lasers, their quantum efficiency could be much greater than one due to the so-called cross-relaxation energy transfer process between thulium ions, in which two ground-level thulium ions can be excited to the upper lasing level by absorbing only one pump photon near 800 nm. This process can only occur in the laser medium with high Tm-ions concentration. Multicomponent silicate glass can be an ideal host since Tm-ions can be highly doped into silicate glass. With high Tm-ions doping concentration, both pump absorption efficiency and gain per unit length of Tm-doped silicate fiber increase accordingly, which allows efficient laser operation in a short piece of doped active fiber. We have demonstrated a mode-locked fiber laser using a piece of 30 cm Tm-doped silicate glass fiber [7]. So far the reported Tm–Ho-codoped fibers have the glass host of either silica glass or fluoride glass. We use the multicomponent silicate glass as the host for Tm–Ho fiber, which offers higher doping concentration as well as good mechanical strength. Heavily Tm and Ho codoped silicate glasses are expected to benefit from the cross relaxation process as observed in Tm only doped silicate glass.

II. Experimental Results

In this demonstration, Tm–Ho-codoped silicate glasses, undoped cladding glasses, and fiber preforms were designed and fabricated in house. The thulium and holmium doping concentrations are 6 wt% and 0.4 wt% respectively. Rod-in-tube technique was used to fabricate single-mode double glass-cladding fibers. The fiber has core diameter of 10.5 μm and core numerical aperture (NA) of 0.12 with the V number of 1.94 at the wavelength of 2.06 μm. The inner cladding has the diameter of 125 μm and NA of 0.58 to efficiently couple pump light from pump combiner output fiber (125 μm, 0.46 NA). This large

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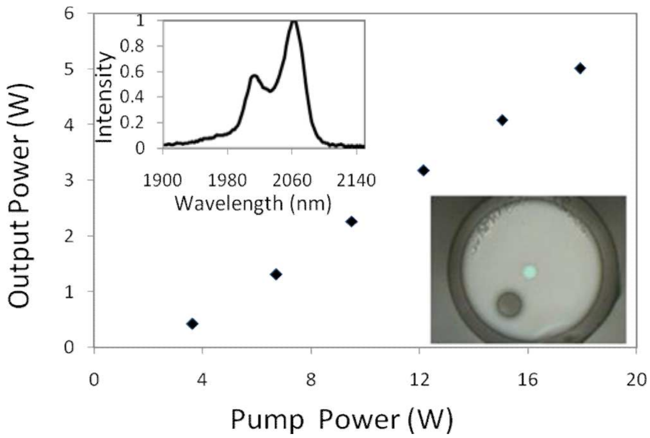

Fig. 1. Tm–Ho-codoped cw fiber laser output power as a function of 798-nm pump power. Top-left inset is a typical ASE spectrum of Tm–Ho-codoped silicate fiber with cladding pump at $\sim$ 800 nm. Bottom-right inset is the microscope image of the fiber facet.

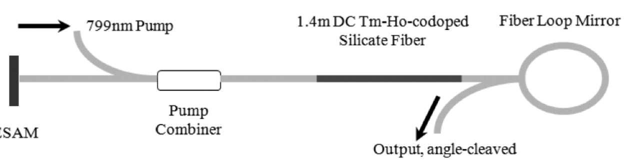

Fig. 2. Schematic of mode-locked Tm–Ho-codoped silicate fiber laser.

cladding NA benefits from high refractive indexes of core and first cladding glass, which are 1.6412 and 1.6367 respectively (measured at 589 nm). The outer cladding is a glass cladding with the diameter of 150 μm. The fiber structure can be seen from a microscope image of the fiber facet in the bottom-right inset of Fig. 1. A solid insertion rod in the inner cladding is used to enhance cladding-pump absorption [7].

A typical spectrum of amplified spontaneous emission (ASE), measured from a piece of 8-meter-long Tm–Ho-fiber cladding-pumped with a $\sim$ 800 nm pump LD, is shown in the top-left inset of Fig. 1. The spectrum is presented in a linear scale and it exhibits $\sim$ 70 nm bandwidth and peak wavelength at 2060 nm. Comparing to the fluorescence spectrum of the Tm-doped fiber shown in [13], which has the peak at $\sim$ 1900 nm, our Tm–Ho-fiber clearly shows a strong emission from Holmium ions. Continuous wave (cw) laser performance was characterized with a piece of 1.2 m long Tm–Ho-fiber. The laser cavity is closed with a dielectric mirror coated on a fiber end (HR at 2.06 μm and AR at 800 nm) and a straight cleave end (acting as output coupler). Multiple multimode laser diodes at 0.8 μm were used to cladding-pump this fiber laser. The pump absorption of the fiber at 793 nm is 10 dB/m. The output power as a function of the absorbed pump power is shown in Fig. 1. A slope efficiency of 32% was obtained from this laser.

The Experiment setup of the mode-locked Tm–Ho-fiber laser, shown in Fig. 2, is similar to that in our previous demonstration on mode-locked Tm-fiber laser [7]. The linear laser cavity consists of a SESAM, a pump combiner, a piece of 1.4 m long double cladding Tm–Ho-codoped silicate fiber and a fiber loop mirror. The active fiber was cladding-pumped by a single unit of a laser diode through a multimode pump combiner. The fiber loop mirror has an estimated reflectivity of $\sim$70% around 2 μm. Because of a large difference in refractive indexes, we made an angle-fusion-splicing between the Tm–Ho-codoped silicate fiber and passive silica fibers (commercial single-mode silica fibers), preventing from any spurious reflection that could be detrimental to mode-locking operation. The fiber output end was also angle-cleaved to eliminate back reflection. Each angle-cleaved splicing has estimated loss of $\sim$ 1.5 dB. The input end of the pump combiner signal fiber was directly butt-coupled to a Sb-based SESAM, which is the key element to start and maintain mode-locking operation of the laser. The Bragg mirror in the SAM is composed of 18.5 pairs of $AlAs_{0.08}Sb_{0.92}/GaSb$ quarter-wavelength layers deposited by molecular beam epitaxy on GaSb substrate. This mirror structure provides high reflectivity over a wavelength band larger than 400 nm. $Ga_{0.8}In_{0.2}Sb/GaSb$ quantum-wells placed within a GaSb microcavity account for saturation absorption [14].

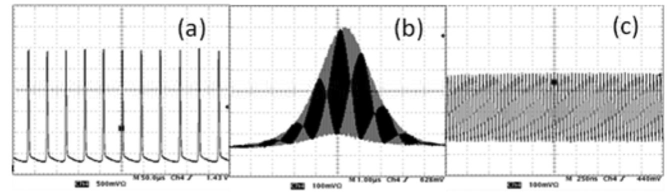

Fig. 3. Tm–Ho-fiber laser pulse trains. (a) Q-switching. (b) Q-switched mode-locking. (c) Mode-locking.

Like a typical soliton fiber laser, we have observed that the laser went through several working regime as the pump power was increased. After reaching the 4 W threshold of cw operation, higher pump power leads to Q-switching and Q-switched mode-locking, which results from relatively high modulation depth of our SESAM. Further increasing the pump power to 4.15 W, self-started cw mode-locking was obtained. Fig. 3 shows typical pulse trains of Q-switching, Q-switched mode-locking and cw mode-locking, which were recorded with a $\sim$ 15 MHz InGaAs photodiode and a 500 MHz bandwidth oscilloscope. In the Q-switching regime, the repetition rate increases and the pulsewidth decreases with increasing pump power.

CW mode-locking operation occurred in the laser when the pump power was higher. The repetition rate of the mode-locked pulses was $\sim$ 24.4 MHz, which was characterized with a RF spectrum analyzer. The RF spectrum at the repetition frequency has a-few-Hz linewidth and more than 60 dB signal to noise ratio. The maximum average output power of the laser in single-pulsing mode-locking regime is $\sim$ 10 mW. Higher pump power causes the laser to operate in multipulsing regime, in which multipulses circulating in the cavity could either space evenly or bunch up.

Multi-pulsing operation or cw mode-locking breakthrough is a well-known characteristic of soliton fiber lasers, which happens when intracavity laser pulse energy is higher than the soliton energy defined by laser cavity dispersion and nonlinearity. The soliton energy can be calculated by the equation [15], $E_{soliton} = 3.11\lambda^2/2\pi c\gamma|D_{\rm ave}|/\tau_{\rm FWHM}$. We can calculate the soliton energy in our laser, where the center wavelength $\lambda = 2.06$ μm, the estimated nonlinear coefficient $\gamma \sim 0.9$ W^{-1}km^{-1} (assuming the nonlinear refractive index is

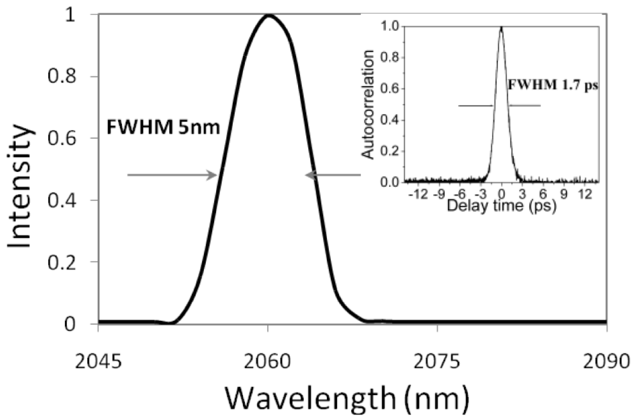

Fig. 4. Mode-locked Tm–Ho-fiber laser spectrum. Inset is the autocorrelation trace of the mode-locked laser pulses.

2.2E-20 m^2/W for both silicate and silica fiber), the estimated average dispersion $D_{\rm ave} = 60$ ps/nm/km, and the FWHM pulsewidth $\tau_{\rm FWHM} = 1.1$ ps. Accordingly the calculated soliton energy is $\sim$0.42 nJ, which is in well agreement with the measured result for the mode-locked laser with 10 mW maximum average output power.

The optical spectrum of the mode-locked laser at the output of 10 mW is shown in Fig. 4 The central lasing wavelength is around 2.06 μm, which corresponds to the peak of ASE shown in Fig. 1 inset. The full width half maximum (FWHM) is ~ 5 nm. The pulsewidth was characterized with a commercial autocorrelator (Femtochrome Research Inc.). The intensity autocorrelation of pulses at 10 mW output is shown in inset of Fig. 4. The FWHM of autocorrelation trace is ~ 1.7 ps, and it corresponds to a FWHM pulsewidth of 1.1 ps for sech^2-shape pulses. The time-bandwidth product of 0.38 indicates that pulses are close to transform-limited. With better dispersion management, for example by reducing the length of passive anomalous-dispersion fiber and inserting a piece of normal dispersion fiber near 2 μm, femtosecond mode-locked pulses are expected [16].

III. Conclusion

In summary, we have demonstrated a passively mode-locked fiber laser at 2.06 μm using our newly developed Tm–Ho-codoped silicate fiber and Sb-based SESAM. Laser pulses with 0.41 nJ pulse energy and 1.1 ps duration were obtained. Shorter pulses are expected with appropriate dispersion compensation. The pulse from the oscillator can be amplified with our in-development dc Tm–Ho silicate fiber, which has large mode area and high gain per unit length. With peak power and energy further scaled, the pulsed laser will be very useful for OPO and supercontinuum generation in mid-IR wavelength range.

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