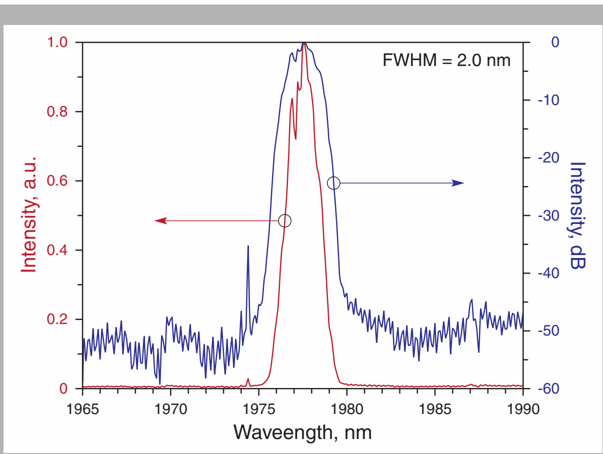
**Abstract:** We have demonstrated a mode-locked thulium-doped fiber laser with a narrow bandwidth and high pulse energy using a semiconductor saturable absorption mirror (SESAM). The laser generates sub-nanosecond pulses with a repetition rate of 39.8 MHz, average power of 150 mW, pulse energy of 3.8 nJ and spectrum width of 2 nm which should be attractive for pump sources to generate mid-infrared. To the best of our knowledge, this is the first report on a 2 $\mu$m mode-locked fiber-oscillator with a narrow spectral width and highest pulse energy in the all-anomalous-dispersion regime.




Typical mode-locking spectrum on linear (red) and logarithmic (blue) scales



# Mode-locked thulium-doped fiber laser with a narrow bandwidth and high pulse energy

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**Key words:** fiber lasers; thulium-doped fiber; passively mode-locking; narrow bandwidth

## 1. Introduction

Ultrafast passively mode-locked fiber lasers at ~1 and ~1.55 $\mu$m wavelength range have been studied extensively because of their wide applications in metrology, biomedicine, spectroscopy and signal processing. Recently, thulium(Tm)-doped fiber lasers operating at ~2 $\mu$m also have attracted considerable attention due to their advantages such as broad emission spectrum (>200 nm) [1,2] and high efficiency caused by cross-relaxation process [3]. Tm fiber lasers have many potential applications in eye-safe laser radar, medicine, remote sensing, and 3–5 $\mu$m optical parameter oscillators (OPOs).

To date, mode-locked Tm-doped fiber lasers with short duration and high energy have been successfully generated by nonlinear polarization evolution (NPE) [4–9], carbon nanotubes (CNTs) [10–12], and semiconductor saturable absorption mirror (SESAM) [13–17] in negative and positive dispersion regimes, respectively. Benefiting from the compactness and polarization independence, SESAM have been widely used to initiate and stabilize the mode-locked pulses. Sharp and his co-workers [13] reported an excellent mode-locked Tm-doped fiber laser with the shortest pulses in the linear cavity. Wang and his colleagues [14,15] also obtained a 2 $\mu$m soliton laser with highly Tm-doped and Tm-Ho-codoped silicate fibers by SESAM, yielding the pulse energy of 0.76 and 0.41 nJ, respectively. Re-

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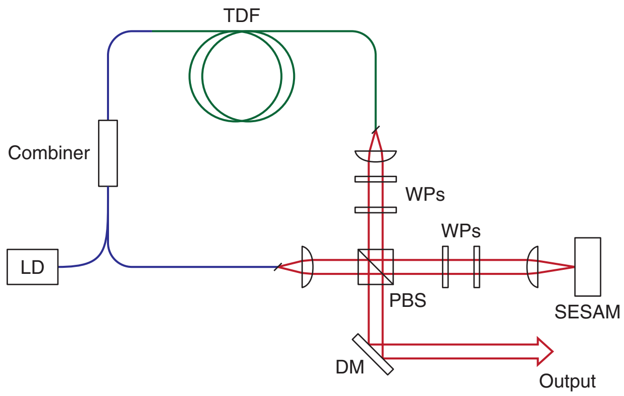


**Figure 1** (online color at www.lasphys.com) Schematic of Tm-doped fiber laser. SESAM – semiconductor saturable absorption mirror, PBS – polarization beam splitter, WPs – half-/quarter-wave-plates, TDF – Tm-doped fiber, Combiner – pump combiner, LD – laser diode centered at 793 nm, and DC – dichroic mirror (HR 2000 nm/AR 793 nm)

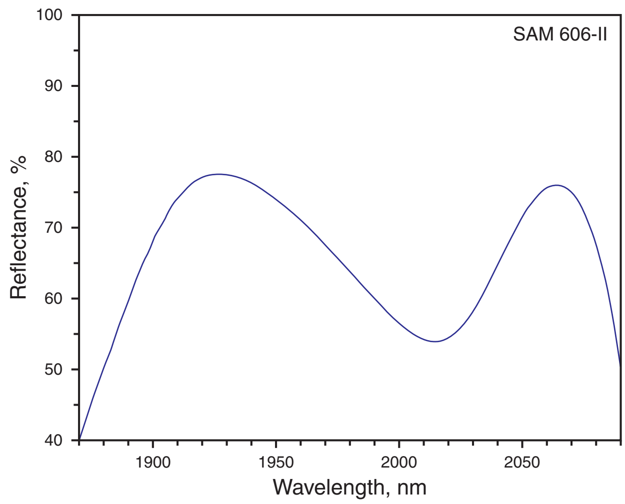


**Figure 2** (online color at www.lasphys.com) Intensity spectral reflectance of the SESAM

cently, Gumenyuk et al. [16] demonstrated the first dissipative dispersive-managed soliton fiber laser with the pulse energy of 1.7 nJ, operating at 2 $\mu$m by employing a chirped fiber Bragg grating and SESAM.

As we know, the spectral width of a mode-locked laser is much larger than the continuous wave (CW) laser and/or Q-switched laser. Most attention has been focused on the mode-locked fiber lasers with broad bandwidth and short duration in the past [4–17], while only a few studies have been reported on mode-locked fiber lasers with narrow bandwidth. However, mode-locked lasers with narrow bandwidth are good pump sources to generate mid-infrared due to its better phase matching than femtosecond pulses. McFerran et al. [18] used a SESAM in a Yb-Er fiber laser to achieve mode-locked pulses with a bandwidth of $\sim$2.6 nm and a repetition frequency in excess of 2 GHz at a central wavelength of 1.535 $\mu$m. By using the NPE technology, Kobtsev et al. [19] presented high-energy single chirped pulses with spectral bandwidth being $\sim$2 nm at 1075 nm. As for the Erbium-doped mode-locked fiber laser with ultra-low repetition rate, Chen et al. [20] employed a high modulation depth SESAM and generated highly-chirped pulses with a narrow spectral width of $\sim$3.2 nm, yielding the pulse energy up to 14 nJ. Furthermore, Tian and his coworkers [21] reported a SESAM-mode-locked fiber laser with large pulse energy and a much narrower spectrum bandwidth of 0.3 nm operating at 1068 nm. This laser generated strongly chirped pulses with duration of 910 ps, energy of 4.3 nJ and repetition rate of 397 kHz. More recently, Liu et al. [22] demonstrated a stable narrow bandwidth SESAM-mode-locked Yb-doped fiber laser with a high repetition rate imposed by a narrow bandwidth fiber Bragg grating.

However, reports on narrow bandwidth (<3 nm) in a mode locked Tm-doped fiber laser are rare. In this letter, we focused on experimental realization of a stable mode-locked fiber laser with a narrow bandwidth and large pulse energy achieved by SESAM in a cavity of sigma configuration. Without any dispersion compensation or spectral filtering components, we obtained a mode-locked Tm-doped fiber laser with repetition rate of 39.8 MHz, average power of 150 mW, pulse energy of 3.8 nJ, and spectral width of 2 nm. To the best of our knowledge, this is the first report on a narrow bandwidth and highest pulse energy from a mode-locked Tm-doped fiber laser in all-anomalous-dispersion regime.

## 2. Experimental setup

The experimental setup is shown in Fig. 1. The laser system had a cavity of sigma configuration, formed by a SESAM, a pump combiner, a piece of double-cladding Tm-doped silica fiber, a polarization beam splitter and wave plates. The key component to initiate and maintain mode-locking operation of the laser was a piece of SESAM. The SESAM (BATOP Company, sam-2000-44-x) was based on InGaAs quantum wells. It had a modulation depth of 26%, a saturation fluence of 130 $\mu$J/cm$^2$, and a recovery time of 500 fs. Fig. 2 presents the low intensity reflectance spectrum of the SESAM [23], which exhibits an absorption band extending from 1.92 to 2.07 $\mu$m, with its center at 2.01 $\mu$m. The Tm-doped fiber had a core/cladding diameter of 10.3/125 $\mu$m and corresponding numerical apertures (NA) of 0.15/0.46, respectively. The nominal pump absorption was 3 dB/m at 792 nm; hence, an active fiber length of $\sim$2 m was chosen to ensure efficient pump absorption and relatively low reabsorption at the lasing wavelength. The pump source was a LD with 0.22 NA and 105/125 $\mu$m fiber pigtail, and a multimode

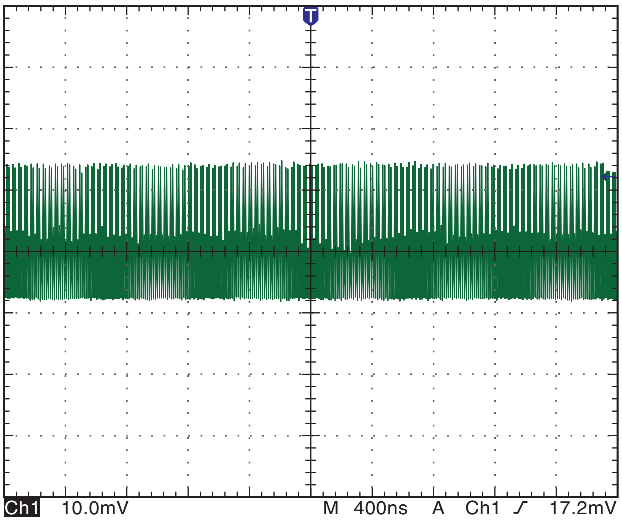


**Figure 3** (online color at www.lasphys.com) A typical experimentally measured mode-locked pulse trace by high-speed oscilloscope

pump combiner was used to deliver pump light into the Tm-doped fiber. A 2-m-long nominal Tm-fiber-matched passive fiber pigtail (10/125 $\mu$m, 0.15/0.46) of combiner was fusion spliced to the active fiber and all fiber ends were angle cleaved to eliminate back reflection. A polarization beam splitter (PBS) combined with half and quarter wave plates were employed to control the output ratio of laser power. Three lens with identical focal length ($f = 40$ mm) were used to focus and collimate the beam in the cavity. The cavity had an overall optical path length of $\sim 7.5$ m corresponding to a fundamental repetition rate of $\sim 40$ MHz. All fibers in cavity had anomalous dispersion and the total dispersion of the cavity was estimated to be $\sim -0.3$ ps$^2$.

## 3. Experimental results and discussions

Mode-locking of the oscillator was achieved by SESAM. The laser system had a threshold of 1.5 W (launched pump power) for the CW laser operation. The relatively high threshold was mainly due to the relatively large loss from the fusion-splicing joint caused by the slight mismatch between active fiber and passive fiber pigtail. With the further increase of pump power pulse trains of Q-switching and instable Q-switched mode-locking were sequentially observed. Pumped at a power of 2.1 W (launched pump power), stable and clean CW mode-locked pulses were achieved by carefully adjusting the wave plates. Once mode-locking was achieved by the initial adjustment of wave plates, the pulses were self-starting and did not require any tuning of wave plates and incident beam size on the SESAM when the pump power was switched on.

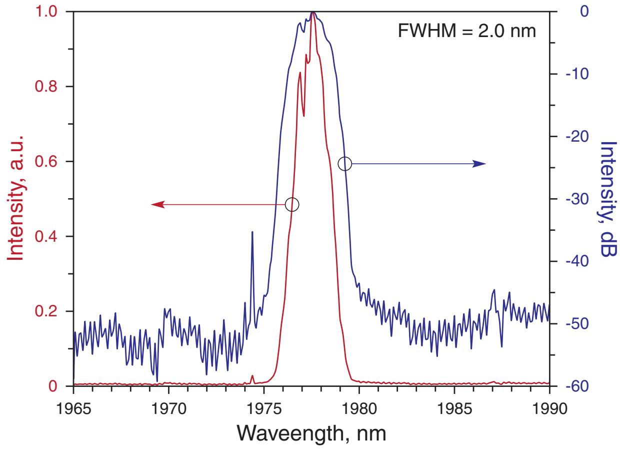


**Figure 4** (online color at www.lasphys.com) Typical mode-locking spectrum on linear (red) and logarithmic (blue) scales

Tests had shown that the system can maintain stable CW mode-locking for many hours without Q-switching or Q-switched mode-locking. To further increase the launched pump power to higher than 2.5 W, mode-locked pulses became instable and multiple pulses appeared after slightly tuning the wave plates.

The mode-locked pulse trains were measured using the high-speed oscilloscope (6 GHz bandwidth, 35 ps detector) and shown as Fig. 3. The measured round-tripe time was $\sim 25.3$ ns and the corresponding fundamental repetition rate was around 39.8 MHz, which indicates that the oscillator operated in fundamental mode-locking mode. Average output power increased with the pump power as well as the pulse energy. The measured minimum output average power was 70 mW corresponding to the pulse energy of 1.8 nJ. The maximum power of was 150 mW and the pulse energy was high as 3.8 nJ, which was much larger than that of conventional solitons.

The optical spectrum of the output pulses was analyzed using a 0.55 m monochromator containing a 300 lines/mm grating blazed at 1800 nm and a TE-cooled InGaAs detector (0.8 – 2.2 $\mu$m), and the resolution of the monochromator was estimated to be $\sim 0.9$ nm at 2 $\mu$m. As shown in Fig. 4, the central wavelength is 1978 nm, and the full width at half-maximum (FWHM) is $\sim 2$ nm. The relatively smooth spectrum and the missing of the Kelly sidebands show that the mode-locked laser pulses in our experiment may be different from the conventional solitons in the all-anomalous-dispersion regime.

The duration of the output mode-locked pulse was measured by the commercially available autocorrelator (APE Company). As shown in Fig. 5, the FWHM of the autocorrelation trace is 1150 ps, and the corresponding pulse duration is $\sim 815$ ps assuming a Gaussian pulse shape due to the best fitting for the autocorrelation trace. The calculated time–bandwidth product of pulse was 125, indicating that the output mode-locked pulse was highly

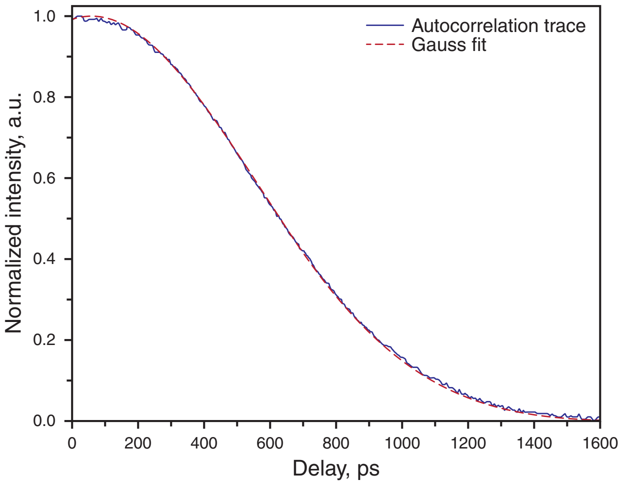


**Figure 5** (online color at www.lasphys.com) Intensity autocorrelation trace of output pulses

chirped. We expected that the duration of pulse can be shortened down to several picoseconds with dispersion compensation [5].

The mode-locked pulses obtained in all-anomalous-dispersion regime were characterized by long duration, large pulse energy, high chirp, and narrow bandwidth, which are different from conventional solitons. We attribute them to the complex balance of the spectral filtering effects of SESAM [21], nonlinearity and large anomalous dispersion of fiber. The corresponding exact mechanism will be our future work.

## 4. Conclusions

Without any dispersion compensation or spectral filtering components, we have demonstrated a SESAM-mode-locked Tm-doped fiber laser with a narrow bandwidth and high pulse energy in the all-anomalous-dispersion regime. The laser generated sub-nanosecond pulses with a repetition rate of 39.8 MHz, average power of 150 mW, pulse energy of 3.8 nJ, and bandwidth of 2 nm. To the best of our knowledge, this is the first time to report a 2 $\mu$m mode-locked fiber laser with a narrow spectrum and largest pulse energy in all-anomalous-dispersion regime.

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