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Synchronously Pumped Mode-Locked 1.89 μm Tm-Doped Fiber Laser with High Detuning Toleration *

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We propose and demonstrate a synchronously pumped mode-locked Tm-doped fiber (TDF) laser without any extra mode-locking elements. Pumped by a 1.56 μm pulse fiber laser, the TDF laser generates 1.17 ps pulses with a spectral width of 9.7 nm and a repetition rate of 9.33 MHz. The emission wavelength is tunable along with the cavity length detuning in a wide range of 3 mm. The high detuning toleration is beneficial to achieve high temperature and vibration stability in all-fiber configuration lasers.

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Mode-locked thulium-doped fiber (TDF) lasers operating within 1.8–2.1 μm have attracted intense attention in recent years[1] because of their potential applications in medicine,[2] plastic material processing[3] and remote sensing.[4] A range of substances show strong absorption in the near-infrared and mid-infrared, such as water and polymers. Since water is the major constituent of the human body, 1.8–2.0 μm Tm-doped laser sources can be available for dermatology and surgery as efficient and precise optical scalpels.[5,6] Similarly, strong absorption characteristics of polymers in the mid-infrared makes high average power and widely wavelength tunable TDF lasers[7] viable for laser processing of polymers. In addition, the lasers operating near 2 μm, which cause low damage to the retina, are ideal eye-safe sources in free-space sensing applications.[8]

In the last two decades, demonstrations of mode-locked TDF lasers have been widely reported, including passive and active mode-locking. Passively mode-locked TDF lasers were mainly based on nonlinear polarization evolution,[9] nonlinear optical loop mirror,[10] and saturable absorbers, such as semiconductor saturable absorber mirrors,[11] carbon nanotubes[12,13] and so-called two-dimensional materials (like graphene).[14–16] Actively mode-locked TDF lasers generally utilized optical or electrical modulators inside or outside the cavity. In Ref. [17], Wang *et al.* demonstrated a TDF laser with a pulse width of 446 ps and a repetition rate of 12.099 MHz through an intracavity optical phase modulator, although the modulator caused a high insertion loss. Active mode-locking via pump modulation was used for generating 1.93 μm pulses with a pulse duration of 4.4 ps and a spectral bandwidth of 0.9 nm in Ref. [18], which utilized a pump modulator to achieve a pump-induced gain modulation. However, the laser containing an outer cavity modulator not only led to higher costs, but also suffered from environmental instability due to a low cavity length detuning toleration, which limits the potential of the laser in some applications, such as high order harmonic mode-locking.[19]

In this Letter, we demonstrate a 1.89 μm TDF laser synchronously mode-locked by pump-induced phase modulation without any electrical or optical modulators. Pumped by a 1.56 μm fiber laser with a 660 fs pulse duration, the laser generates ultrafast pulses with a pulse width of 1.17 ps, a spectrum bandwidth of 9.7 nm and a repetition rate of 9.33 MHz. The round-trip cavity length of the TDF laser is able to be changed by ±1.5 mm. Furthermore, a spectral shift of ±7.5 nm is accompanied by the cavity length detuning.

Pump-induced cross phase modulation mode-locking has been investigated previously.[20] In this work, an Er/Yb co-doped fiber laser with a pulse duration of 2.4 ps and a repetition rate of 100 MHz has been demonstrated. Similarly, the generation of 570 fs pulses in a mode-locked Pr-doped fiber laser was realized.[21] However, the lasers mentioned above were both synchronously pumped by Nd:YAG lasers, which lacked compactness and robustness compared to our all-fiber configuration laser.

The experimental setup is shown in Fig. 1, consisting of the Er-doped fiber laser seed, the Er-doped fiber amplifier (EDFA), and the TDF laser. The pump of the TDF laser is composed of the EDFA and the Er-doped fiber laser seed based on nonlinear polarization rotation (NPR) mechanism. The NPR cavity consists of a 1-meter-long Er-doped fiber (EDF, Liekki Er110-4/125), a 980/1550 nm wavelength division multiplexer (WDM), a ∼20 meter-long single mode fiber (SMF, Corning SMF-28e), a polarization sensitive isolator (PS-ISO), two polarization controllers (PC1 and PC2), and an 85:15 output coupler (OC). The net dispersion of the NPR cavity is

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calculated to be $-0.4\,\mathrm{ps}^2$ where fiber dispersion is $-21\,\mathrm{ps}^2/\mathrm{km}$ of SMF-28e and $12\,\mathrm{ps}^2/\mathrm{km}$ of Er-110 at 1560 nm. In addition, The TDF laser cavity consists of a section of 5-meter-long TDF (Nufern SM-TSF-9/125), a 1550/2000 nm WDM, a ∼16 meter-long SMF (Nufern SM1950), a polarization insensitive isolator (PI-ISO), a 60:40 OC and a fiber delay line, which is used to match the cavity length between the NPR cavity and the TDF laser cavity. The net dispersion of the TDF laser cavity is approximately equal to $-1.72\,\mathrm{ps}^2$, since the active fiber and the SM1950 fiber have dispersions of $-87\,\mathrm{ps}^2/\mathrm{km}$ and $-80\,\mathrm{ps}^2/\mathrm{km}$ at 1900 nm.

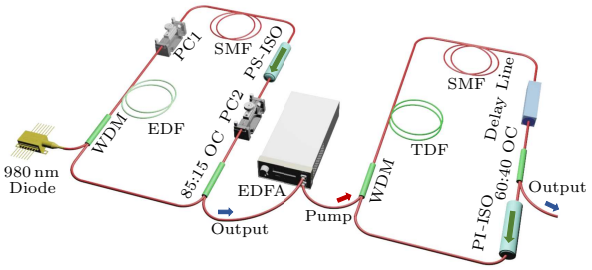


Fig. 1. Experimental setup of the synchronously pumped mode-locked TDF laser.

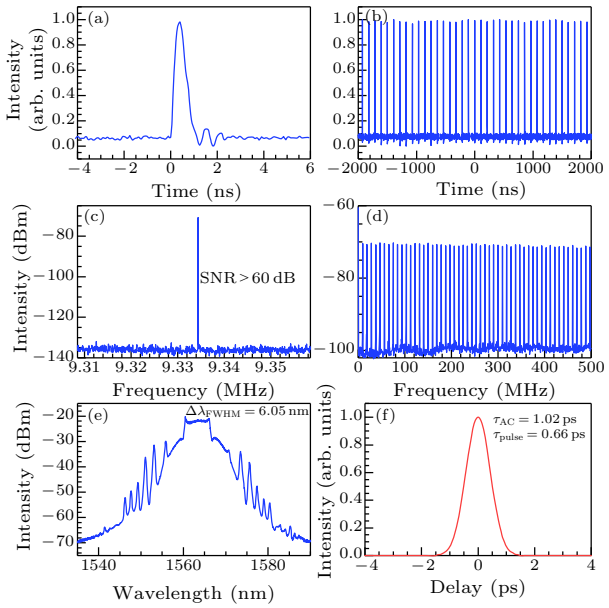


Fig. 2. (a) Single pulse and (b) pulse train of the pump; (c) rf spectrum with a span of 50 kHz and RBW of 1 Hz; (d) rf spectrum with a span of 500 MHz and RBW of 1 kHz; (e) optical spectrum; and (f) autocorrelation trace of the pump pulse.

In our experiment, the output spectrum and pulse trains were measured with an optical spectrum analyzer (OSA, Yokogawa AQ6375) and a digital oscilloscope (LeCroy WaveRunner 640Zi, 4 GHz bandwidth) along with a photon detector (EOT-5000F, 12.5 GHz bandwidth), respectively. The oscillating frequency and stability were monitored by an rf spectrum analyzer (AV4021). The pulse durations were characterized by an autocorrelator (APE PulseCheck SM600).

The NPR-based seed laser achieves stable mode-locking pulses with proper adjustment of PC1 and PC2. The single pulse and pulse train measured by the oscilloscope are shown in Figs. 2(a) and 2(b), respectively. The corresponding rf spectra, consisting of a 50 kHz span spectrum in 1 Hz resolution bandwidth (RBW) and a 500 MHz span spectrum in 1 kHz, are depicted in Figs. 2(c) and 2(b), respectively. The repetition rate is measured to be 9.33 MHz, corresponding to a 21.44-meter-long cavity length. The signal-to-noise ratio (SNR) is larger than 60 dB. As shown in Fig. 2(e), the pulse pump spectral width of full width at half maximum (FWHM) is measured to be 6.05 nm with 0.05 nm resolution. The Kelly sidebands in the spectrum indicates that the oscillator worked in soliton regime. Moreover, the autocorrelation trace of the single pulse is shown in Fig. 2(f). Under a hyperbolic-secant fitting, the pulse duration is measured to be 0.66 ps. Through amplifying by the EDFA, the pulses achieve sufficient power to pump the TDF laser and generate strong pump-induced cross phase modulation.

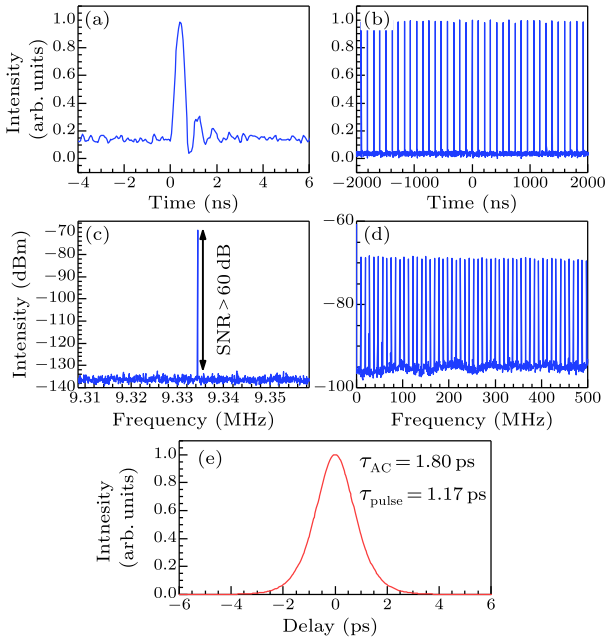


Fig. 3. (a) Single pulse and (b) pulse train of output pulse; (c) rf spectrum with a span of 50 kHz and RBW of 1 Hz; (d) rf spectrum with a span of 500 MHz and RBW of 1 kHz; and (e) autocorrelation trace of the output pulse.

As the amplified 1.56 μm pulses are launched through the TDF laser, it results in the generation of synchronously mode-locked laser pulses at the output port. Stable self-starting mode-locked pulses appear when the amplified pulse pump power increases to 225 mW. At the maximum achievable pump power of 402 mW, the average output power of 6.58 mW is observed. Figures 3(a) and 3(b) show the single pulse profile and pulse train of the output, respectively. The rf spectrum with a span of 50 kHz and an RBW of 1 Hz

is shown in Fig. 3(c), and the rf spectrum with a span of 500 MHz and an RBW of 1 kHz is shown in Fig. 3(d). The SNR was larger than 60 dB at the fundamental frequency, which indicates the stable single-pulse mode-locking operation. The repetition rate is also measured to be ∼9.33 MHz, since the cavity length of the TDF laser approximately matches the cavity length of the seed laser. The autocorrelation trace of the output pulse is depicted in Fig. 3(e), showing a pulse duration of 1.17 ps under the sech^2 assuming. The time-bandwidth product is calculated to be 0.96, which suggests that the pulse width can be further compressed.

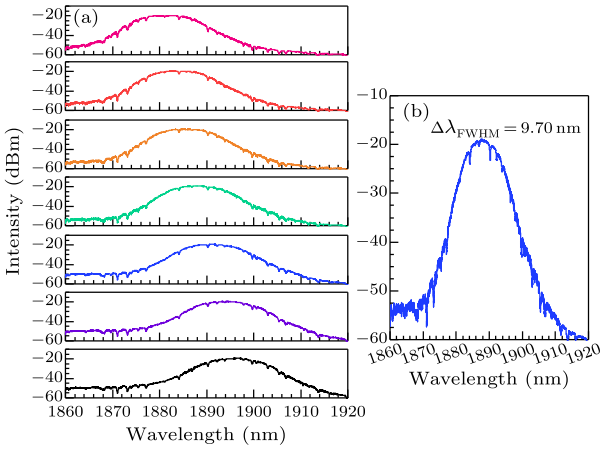


Fig. 4. (a) The series of output spectra with central wavelengths from 1881 nm to 1895 nm in a ∼2 nm spacing. (b) The output spectrum at the central wavelength of 1888 nm.

By adjusting the fiber delay line in the TDF laser cavity, the cavity length can be changed by ±1.5 mm without loss of mode-locking state, which is better than that in previously reported synchronously mode-locking lasers.[16–18] High cavity length detuning toleration is beneficial to reducing the environmental instability caused by the cavity length mismatch. A spectrum shift is observed along with the cavity length detuning. As shown in Fig. 4(a), continuous tuning from 1881 nm to 1896 nm of the central wavelengths is obtained by adjusting the fiber delay line. The spectral profile does not change during the central wavelength tuning. Figure 4(b) plots the zoomed-in spectrum with the central wavelength of 1888 nm. The spectral width of FWHM is measured to be 9.7 nm with 0.05 nm resolution, which supports transform-limited pulse durations as short as 385 fs under the assumption of sech^2 pulse profile. The absorption dips on the spectra originate from the strong water absorption lines in atmospheric air. Furthermore, it is worth mentioning that the change of pulse duration is not observed when tuning the cavity length of TDF laser.

As mentioned in Refs. [20,22], the group velocity dispersion of the TDF laser cavity is given by

$$\overline{\beta_2} = -\frac{\Delta L_{\rm t}}{L_{\rm t} v_{\rm gs} \Delta\omega}, \tag{1}$$

where $L_{\rm t}$ is the fiber round-trip length, $v_{\rm gs}$ is the group velocity, and $\Delta\omega$ is the frequency shift. For a cavity detuning of 1.5 mm and a spectral shift of 7.5 nm, the net dispersion is calculated to be -1.87 ps^2, which agrees well with the estimates given above.

In conclusion, we have successfully realized a 1.89 μm mode-locked TDF synchronously pumped by a 1.56 μm ultrashort pulse laser. Stable mode locking is shown with a pulse width of 1.17 ps, a spectral width of 9.7 nm, and a repetition rate of 9.33 MHz. The maximum cavity length detuning is as large as ±1.5 mm, accompanied with a spectral shift of ±7.5 nm. The all-fiber configuration laser has advantages such as compactness and robustness in practical applications. Furthermore, the presented laser may have potential applications in high order harmonic mode locking due to its resistance to environmental disturbances.

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