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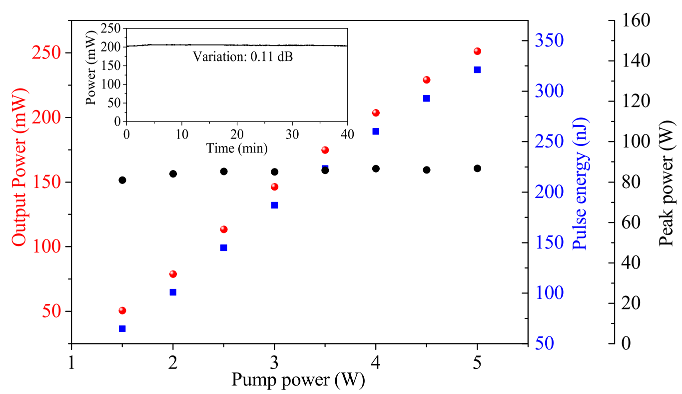

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High Energy Noise-Like Pulse Generation from a Mode-Locked Thulium-Doped Fiber Laser at 1.7 μm

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Abstract: Thulium-doped fiber laser (TDFL) is a versatile platform that can be engineered to produce laser sources with desired performance that target a vast number of applications, however its operation in the 1.7-μm region is still underdeveloped owing to the quasi-three-level nature of TDF emission. In this paper, we report a high energy noise-like pulse generation from a nonlinear polarization rotation (NPR) mode-locked TDFL. By using highly efficient core-pumping at 1650 nm and intra-cavity filtering component, stable mode-locking operation at 1750 nm is realized at a pump threshold of 1.5 W. With increasing the pump power to 5 W, the pulse width is stretched from 0.8 ns to 3.7 ns, while the monitored output power is linearly increased from 50 mW to 251 mW, corresponding to a maximum pulse energy of 321 nJ at the pulse repetition rate of 782 kHz. The long-term and shot-to-shot stability of the output are characterized to be 0.11 dB and 2.8% respectively. Noise-like pulse operation of the laser is confirmed by measuring the autocorrelation trace, which demonstrates a coherent peak on top of a wide pedestal. To the best of our knowledge, this is the first demonstration of high energy noise-like pulse generation from a TDFL at 1.7-μm band, enabling potential applications in for example spectroscopic analysis and material processing.

Index Terms: Fiber lasers, mode-locked lasers.

1. Introduction

In recent years, the popular thulium-doped fiber lasers (TDFL) are expanding their operational wavelength coverage through accessing the 1.7-μm region, where they have previously been hindered by the quasi-three-level nature of TDF emission, which leads to strong re-absorption of short wavelength light [1], [2]. This was driven by a plenty of applications such as deep bio-imaging, spectroscopic analysis and material processing that take advantages of the third near-infrared (NIR3) optical window (1600–1870 nm) for bioimaging and abundant molecular absorptions in this spectral region [3], [4]. Up to now, various demonstrations have been carried out concerning bond-selective detection [5]–[7] and deep bioimaging [8]–[10] through developing laser sources with tailored performance in this spectral region. Since the 1.7-μm wavelength band locates in the gap between the emission spectra of the commonly employed erbium and thulium doped fibers, those laser sources are mainly realized by leveraging fiber nonlinear conversion of lasers in the well-developed telecommunication band. Nevertheless, the nonlinear conversion process generally requires the original source has a very high peak power and comes with tradeoffs regarding the spectral property, power stability and flexibility [5]–[10]. Compared with nonlinearly converted lasers, a laser architecture that exploits the fundamental transition of rare-earth-ions doped in optical fiber (i.e., the energy level transition $^3F_4 \rightarrow {}^3H_6$ in TDF) is advantageous for producing sources with engineerable operating regimes and parameters. It is noted that other than the TDF, bismuth-doped fiber (BDF) has also been demonstrated to enable 1.7-μm laser operation at both continuous-wave (CW) and ultrafast pulsing regime [11]–[13]. However, the relatively low optical gain of BDF requires the laser cavity employs a long gain fiber (generally several tens of meters), limiting the versatility and the achievable power/energy of this type of laser.

To realize efficient 1.7-μm laser generation from TDFL, the key challenge is to circumvent the problem of light re-absorption by the gain fiber and provide enough optical gain for short wavelength laser operation. Using high power core-pumping to realize high fractional population inversion of TDF with optimized length has been proved to be an effective way to produce significant gain in the sub-1800 nm region. In addition, intra-cavity filtering element or wavelength selective component is also indispensable for suppressing unwanted amplified spontaneous emission (ASE) at long wavelength. At present, short wavelength TDFLs have been demonstrated to operate in the CW, soliton mode-locking and gain-switching regimes [14]–[17]. A brief review of the previous work shows that the energetic TDF can provide enough gain for high power/energy generation from a single laser cavity in the 1.7-μm band. While for the soliton mode-locked laser, since its output power is restricted by the peak power clamping effect, an extra amplifier is needed to further scale its power level to meet the practical application need [16]. However, it is more difficult for an amplifier to extract the short wavelength gain from TDF even with high fractional exciting and spectral filtering, since there is no optical oscillation. Therefore, it is preferable to directly obtain a high power/energy output from a single mode-locked TDFL that operates in the 1.7-μm region. A promising scheme is the noise-like mode-locking, which can generate picosecond to nanosecond pulse bunches that contains many ultra-short sub-pulses with random amplitudes and phases resulting from the soliton peak power clamping effect and fiber nonlinearities, and the energy of a single bunch can be largely scaled without breaking [18].

Here we present a high energy noise-like pulse generation from a mode-locked TDFL at a center wavelength of 1750 nm for the first time. Highly efficient core-pumping at 1650 nm and intra-cavity filtering component are employed to realize efficient short wavelength operation of the laser. Under a pump power of 5 W, a maximum output power/pulse energy of 251 mW/321 nJ is obtained with a fundamental pulse repetition rate of 782 kHz. The achieved pulse energy is comparable or even higher than that of the high energy noise-like pulses generated in the well-developed 1.0-μm and 1.5-μm band [19]–[21]. The long-term and shot-to-shot stability of the output are characterized to be 0.11 dB and 2.8% respectively. Noise-like pulse operation of the laser is confirmed by measuring the autocorrelation trace, which demonstrates a coherent peak on top of a wide pedestal.

2. Experimental Setup

Fig. 1 depicts the experimental setup of the short wavelength mode-locked TDFL. Its layout was a ring cavity that formed by a wavelength-division multiplexer (WDM) and a 20/80 optical coupler (OC) with the 80% port guiding the laser output. The gain fiber was a segment of 3-m long TDF (Nufern, SMTSF-9/125), which was optimized through the cutting-back method and core-pumped by a commercial 1650-nm Raman fiber laser. Mode-locking of the laser was initiated and maintained by the association of two quarter-wave plate (QWPs), a half-wave plate (HWP), and a polarization sensitive isolator (ISO) through the nonlinear polarization rotation (NPR) effect. Two collimator (COLs) together with two silver coated mirror (Ms) were utilized to direct light between the fiber part and the NPR assembly and complete the cavity. The insertion loss between the COLs was measured to be around 2.5 dB. In the free space part, a bandpass filter (BPF) with a center wavelength of 1730 nm and a bandwidth of 45 nm was inserted to force the cavity to operate in

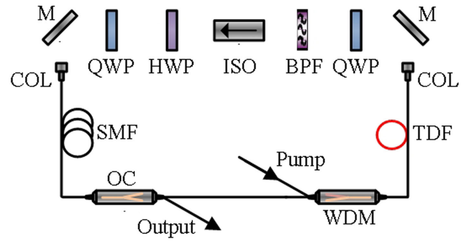

Fig. 1. (a) Diagram of the experimental set up. (b) Detail of the test object used.

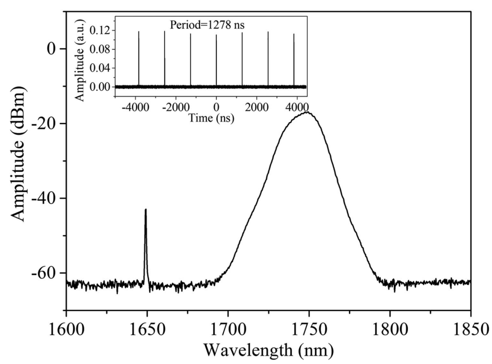

Fig. 2. The optical spectrum and the temporal pulse train (inset) at the pump power of 5 W.

the 1.7-μm band. A segment of 255-m long single mode fiber (SMF) was added to the cavity to enhance the NPR effect, resulting in a total cavity length of ~262-m considering the pigtails of the fiber components and neglecting the free space part. In this way, the total net cavity dispersion was estimated to be -12.2 ps^2 when neglecting the dispersion of the gain fiber, indicating that the laser was operated in the large anomalous dispersion regime [22].

3. Experimental Results and Discussion

When increasing the pump power to around 1.5 W, stable mode-locking operation was obtained through adjusting the waveplates and then maintained with the continuous enhancement of the pump to a maximum power of 5 W. Maintain the state of polarization of the waveplates, self-starting of the mode-locking can be realized when the pump threshold was reached. Under the maximum pump power, the measured optical spectrum of the laser output is shown in Fig. 2, which demonstrates a center wavelength of 1750 nm and a 10-dB bandwidth of 32 nm that was hardly changed with the adjusting of the pump power at 1.5-5 W. Thanks to the BPF, other than a small portion of the residual 1650 nm pump, no any ASE at long wavelength was observed in the spectrum. The inset of Fig. 2 shows the corresponding pulse train, of which the period was measured to be ~1278 ns, confirming the fundamental mode-locking operation of the laser with a repetition rate of 782 kHz. Fig. 3 demonstrates the output power, corresponding pulse energy and peak power of the mode-locked laser versus the increase of the pump power with a step of 0.5 W. The measured power was linearly increased without apparent saturation, and a maximum power of 251 mW and a corresponding maximum pulse energy of 321 nJ were realized. Then the average power stability was characterized through monitoring the laser output at around 200 mW over 40 minutes, and the results is shown in the inset of Fig. 3, which validates the long-term stable operation (variation 0.11 dB) of the mode-locked laser.

The waveform evolution of a single pulse was examined by using a lightwave converter (Hewlett-Packard, 11982A) and a digital oscilloscope (Teledyne LeCroy, SDA8Zi-B) with respect to the

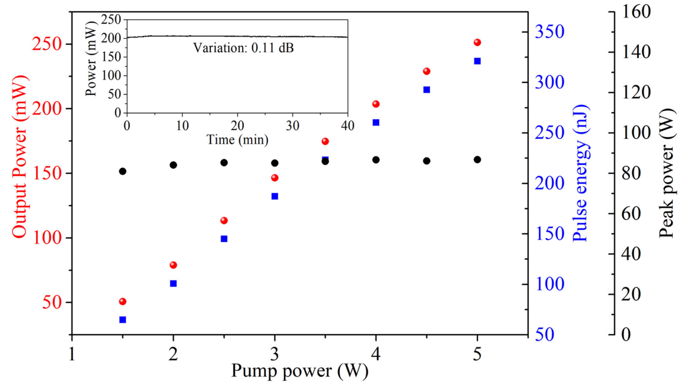

Fig. 3. The output power, corresponding pulse energy and peak power versus the increase of the pump power with a step of 0.5 W. Inset: the monitored average power stability around 200 mW for 40 minutes.

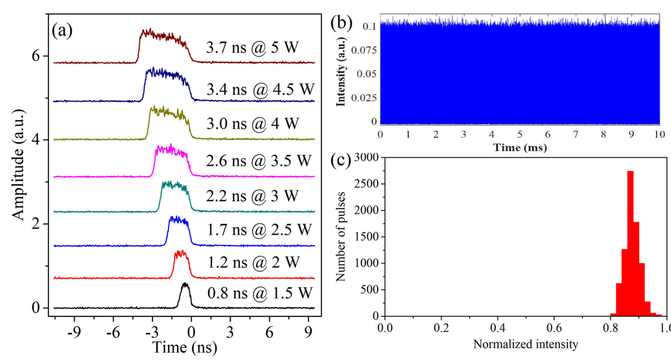

Fig. 4. (a) Evolution the output pulse waveform with the increase of the pump power. (b) The pulse train (over 7820 pulses) at the maximum output power. (c) The corresponding histogram.

increasing of the pump power, and the results is demonstrated in Fig. 4(a). It is observed that the laser pulse basically presents a rectangular shape, and its full width at half maximum (FWHM) monotonously broadened from 0.8 ns to 3.7 ns with enhancing the pump power from 1.5 W to 5 W. The corresponding peak power of the laser pulse was calculated and is shown in Fig. 3. It can be found that the pulse peak power was hardly changed (around 85 W) when increasing the pump power, owing to the peak power clamping effect. It is therefore reasonable to infer that the mode-locked laser was operated in the dissipative soliton resonance (DSR) regime, of which the distinctive feature is the duration of the rectangular pulse linearly tunable with the pump power, while the peak power remains roughly unchanged [23], [24]. Since there are small spikes on top of the pulse waveform, the pulse train was recorded over 10 ms to verify the shot-to-shot stability, as shown in Fig. 4(b). The ratio of standard deviation to the mean (std/mean) of the pulse intensity was calculated to be 2.8% with 7,820 pulses. Fig. 4(c) shows the calculated histogram, which exhibits a narrow band distribution of the pulse intensities and implies stable operation of the laser.

The electrical spectrum at the fundamental repetition rate of 782 kHz is shown in Fig. 5 with a resolution bandwidth (RBW) of 2 Hz. The measured signal-to-noise ratio (SNR) is around 52 dB. The inset of Fig. 5(a) shows the electrical spectral distribution over 1 GHz span using an RBW of 1 kHz. The spectrum demonstrates a periodic-like envelope modulation at a frequency of $\sim$270 MHz, which is equivalent to the reciprocal of the corresponding pulse duration (3.7 ns). This phenomenon has been observed previously in mode-locked laser operating in the DSR regime [25]–[29]. Since DSR is a highly chirped single pulse, there should be no coherent peaks in its autocorrelation trace, which however, is not always characterized in literature [25], [27], [28]. In the current experiment,

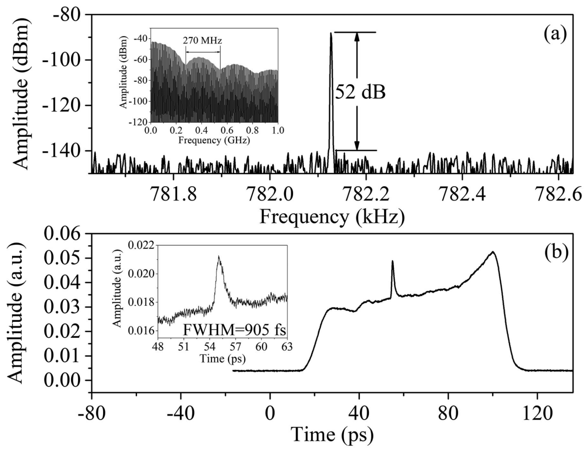

Fig. 5. (a) The electrical spectrum at the fundamental repetition rate of 782 kHz and from 0 to 1 GHz (Inset). (b) Autocorrelation trace of the generated pulse under a pump power of 5 W; Inset: zoom-in of the coherent peak.

an autocorrelator (Femtochrome, FR-103MN) was employed to measure the autocorrelation trace of the pulse at a pump power of 5 W, and the results with a measuring window of 80 ps are demonstrated in Fig. 5(b). Apparently, the trace shows a coherent peak on top of the background level, manifesting a classic signature of the noise-like pulse [30], [31]. The inset of Fig. 5(b) shows the zoom-in of the coherent peak, of which the FWHM is ∼905 fs, corresponding to a duration of 640 fs (assuming a Gaussian profile). Therefore, the measured autocorrelation trace provides a decisive basis that the laser operates in the noise-like regime rather than DSR. In addition, the observed tilting of the measured autocorrelation trace was attributed to the uneven response of the photomultiplier tube (PMT) employed by the autocorrelator in the vicinity of the cutoff wavelength of its response.

4. Conclusion

In conclusion, an NPR mode-locked TDFL that generates high energy noise-like pulses at 1750 nm was demonstrated. Enabled by highly efficient core-pumping at 1650 nm and a BPF that compresses the long wavelength ASE, stable mode-locking operation was obtained at a pump threshold of 1.5 W. Under a maximum pump power of 5 W, the measured output power was 251 mW, corresponding to a maximum pulse energy of 321 nJ at a pulse repetition rate of 782 kHz. With the increase of the pump power, the pulse width was monotonously broadened from 0.8 ns to 3.7 ns. The long-term and shot-to-shot stability of the output were characterized to be 0.11 dB and 2.8% respectively. The SNR of the electrical spectrum at the fundamental repetition rate was measured to be 52 dB. Finally, noise-like pulse operation of the laser was confirmed by measuring the autocorrelation trace, which demonstrates a coherent peak on top of a wide pedestal.

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