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2 μm noise-like mode-locked fiber laser based on nonlinear optical loop mirror[*]

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We report a Tm-doped noise-like mode-locked (NLML) pulsed fiber laser with a compact linear cavity which consists of dual nonlinear optical loop mirrors (NOLMs). The design of dual-NOLM shows both exceptional compactness in construction and distinct flexibility. In this laser, mode-locking can be realized through the nonlinear optical loop mirror technique. Stable noise-like mode-locked pulses with spectral bandwidth of 29.18 nm and pulse energy of 46 nJ are generated at a central wavelength of 1 999.7 nm. Our results indicate that such a simple and inexpensive structure can pave the way for the development of generating supercontinuum with desirable performance.

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Thulium-doped fiber lasers have been extensively investigated due to their widespread applications in optical communications, laser medical treatment, and laser radar[1]. However, the average power and the pulse energy directly from the mode-locked fiber lasers, especially all-fiber lasers, were normally no match for their solid-state counterparts, mainly due to the overdriven fiber nonlinearity and the limited power handling capacities of fiber components.

To design a high-energy mode-locked fiber laser, there are several critical factors that require careful consideration, such as fiber nonlinearity, dispersion, gain, and loss. The balance among these effects determines the pulse-shaping mechanism. Mode-locked fiber lasers are usually categorized by different cavity dispersion distributions. For instance, conventional solitons can be formed as a result of the combination of negative group-velocity dispersion (GVD) and self-phase-modulation (SPM) effects when a mode-locked fiber laser consists of purely anomalous GVD fibers. However, the pulse energy for a single soliton is restricted to ~0.1 nJ due to the soliton area theorem[2,3]. To achieve higher energy pulses, dispersion-managed soliton lasers, or stretched-pulse fiber lasers have been proposed[4]. However, these methods require dispersion compensation fiber and manual adjustment, which are complex and increase the cost of the laser. Moreover, in recent years, noise-like mode-locked (NLML) fiber lasers generating attention[5-7]. According to previous studies, noise-like pulse (NLP) can be acquired easily and used to describe the low-coherent pulse which has femtosecond fine structures inside picosecond/nanosecond pulse packets[8,9].

The saturable absorbers (SAs) are a critical part in mode-locked fiber lasers, SAs can be roughly divided into two major categories depending on the mode-locking mechanism. The first group can be defined as material SAs based lasers, in which the real absorbing materials, e.g., (black phosphorus[10], carbon nanotubes (CNTs)[11] and graphene[12], transition metal dichalcogenides[13]) may face the risks of physical damage under high-energy pulse. At present, semiconductor saturable absorber mirrors (SESAMs)[14] are considered to be one of the most mature and commercial SAs, but SESAMs are expensive for fabrication and have narrow operation bandwidth. Therefore, exploration of the low-cost, broadband and high-performance SAs still remains as an ongoing issue. The second group is referred as nonlinear switched based lasers, in which the transmission or reflectivity property is dependent on the nonlinear phase shift. And the phase shift is induced by nonlinear polarization rotation (NPR)[15], nonlinear optical loop mirror (NOLM)[16-18]. As a result, the mentioned capabilities of pulse self-shaping which is equivalent to real SAs, but usually have higher damage threshold and better flexibility. Among fiber-nonlinearity-based SAs, NOLM requires only a low-cost fiber coupler.

Comparing with conventional figure-8 laser, dual-NOLM fiber laser avoids the requirements of optical isolators, which are usually expensive and vulnerable in high power operation. Based on the considerations stated above, dual-NOLM fiber laser without optical isolators has been adopted in this experiment. Besides, dual-NOLM provide

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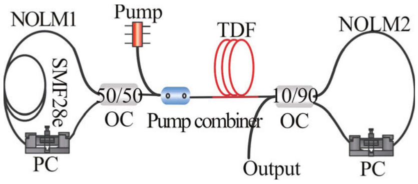
more flexibility in engineering the transmission curve of the artificial SAs than a single NOLM, which is essential in the process of pulse shaping in artificial SAs based mode-locked laser. In Ref.[19], a dissipative soliton (DS) pulse has been presented, the repetition frequency, central wavelength and single pulse energy are 3.5 MHz, 1 082 nm, 80 nJ, respectively. Although there have been several reports of linear cavity lasers based on NOLM, but most of these reports focus on 1 μm and 1.5 μm[20]. However, up to now the 2 μm NLML pulse fiber laser based on the above dual-NOLM has not yet been reported.

In this paper, a Tm-doped fiber laser based on linear cavity has been proposed. 2 μm NLML pulses with high energy and wide spectrum are obtained successfully by using NOLM technology and adjusting the cavity structure. This characteristics research of this laser is quite momentous to practical applications.

A simplified Tm-doped NLML all-fiber laser based on NOLMs is depicted in Fig.1. The laser consists of about 4.5-m-long double-clad Tm-doped fiber (TDF), a 793-nm laser diode (LD) together with a 793/2 000 nm combiner and two NOLMs. The two NOLMs are used as the cavity mirrors to form the laser cavity. NOLM1 is constructed of a 50/50 optical coupler (OC) as a high reflective mirror, and NOLM2 is constructed of a 10/90 OC as a low reflective mirror. Actually, dual NOLMs also act as the artificial saturable absorber to achieve and maintain the mode-locking operation. Polarization controllers (PCs) are generally inserted in the loop to control the linear phase shift that allows mode-locking operation. In addition, a standard SMF28e single-mode fiber about 28 m is inserted for introducing asymmetric gain and enough nonlinear phase shift. The total length of the cavity is about 32.5 m. The total cavity dispersion is about -2.28 ps^2.



PC: polarization controller; TDF: Tm-doped fiber; NOLM: nonlinear optical loop mirror; OC: optical coupler

Fig.1 Experimental setup of the NLML laser

The output characteristics of the laser are measured by a power meter (7Z01560, OPHIR), a 1 GHz digital sampling oscilloscope (WaveRunner 610Zi, Lecroy) with an InGaAs photodetector (ET-5000F, EOT), an optical spectrum analyzer (Omni-λ 750i, Zuolix) with a resolution of 0.05 nm, and a spectrum analyzer (FSL3, Rohde, & Schwarz) with 3 GHz bandwidth.

In order to further investigate the output characteristics of the laser, we record the evolution of the pulse. The laser output power increases monotonously with the launched pump power after reaching the threshold as seen in Fig.2. To be specific, as the launched power reaches the continues-wave (CW) threshold Tm-doped fiber laser (TDFL) operates in two regimes including CW (2.4—5.4 W), NLML (5.5—10.0 W). Thus, mode-locking threshold is obtained as 5.5 W, and the reason for the high value can be explained as follows. In the experiment, the gain medium chose a double-clad fiber, while SMF28e utilized a single-clad fiber, which leads to leakage phenomenon that the utilization rate of pump light is not sufficient. In the further work, we will use a double-clad single-mode fiber for improvement.

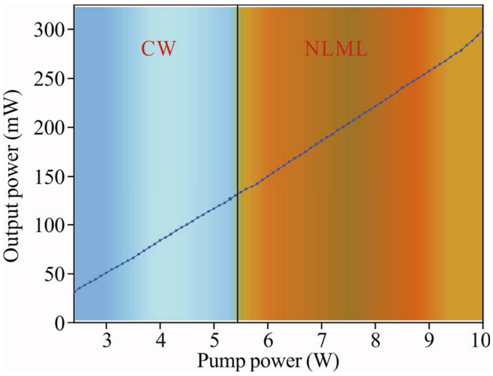


Fig.2 Average output power under different pump power conditions

Fig.3(a) demonstrates the oscilloscope trace of the output pulse train. When the pump power is fixed at 8 W, the adjacent-pulse interval is 153.297 ns, matching well with the cavity length of 32.5 m. The output power of 300.2 mW is obtained at the highest pump power of 10 W. Hence the pulse energy is calculated to be 46 nJ. In all pump power range, the laser always emits single pulse, no pulse breaking or multiple pulse operation is observed as confirmed with the oscilloscope. The results in Fig.3(b) display the corresponding calculated autocorrelation trace has a narrow spike riding on a broad shoulder, and the spike has a temporal width of 985 fs, which is a unique characteristic of the NLP[8]. The NLP is essentially an optical wave packet that contains a bunch of randomly separated sub-pulses with varying amplitudes and pulse widths[9]. Fig.3(c) depicts the measured optical spectrum of the NLML pulse. The broad spectrum has typical shapes of NLML pulse in 1.5 μm and 1.9 μm regions. And the central wavelength and full width at half maximum (*FWHM*) are 1 999.45 nm and 27.73 nm. Increasing the pump power to maximum, the spectrum profile is essentially unchanged but the central wavelength and *FWHM* slight to 1 999.7 nm and 29.18 nm. As presented in the radio-frequency (RF) spectrum of Fig.3(d), the repetition rate of the output pulses is 6.523 MHz. The signal-to-noise ratio (*SNR*) is 50 dB, which indicates a good stability in the NLML operation. The *SNR* of 50 dB which is much higher than the 40 dB typically observed from noise-like mode-locked operation[22], which suggests that low-amplitude noise of inner pulses exist in the noise-like packet. No side lobes are observed in the RF spectrum which are always obvious in the NLML regime[23,24] suggesting the absence of appreciable fluctuations of pulse duration.

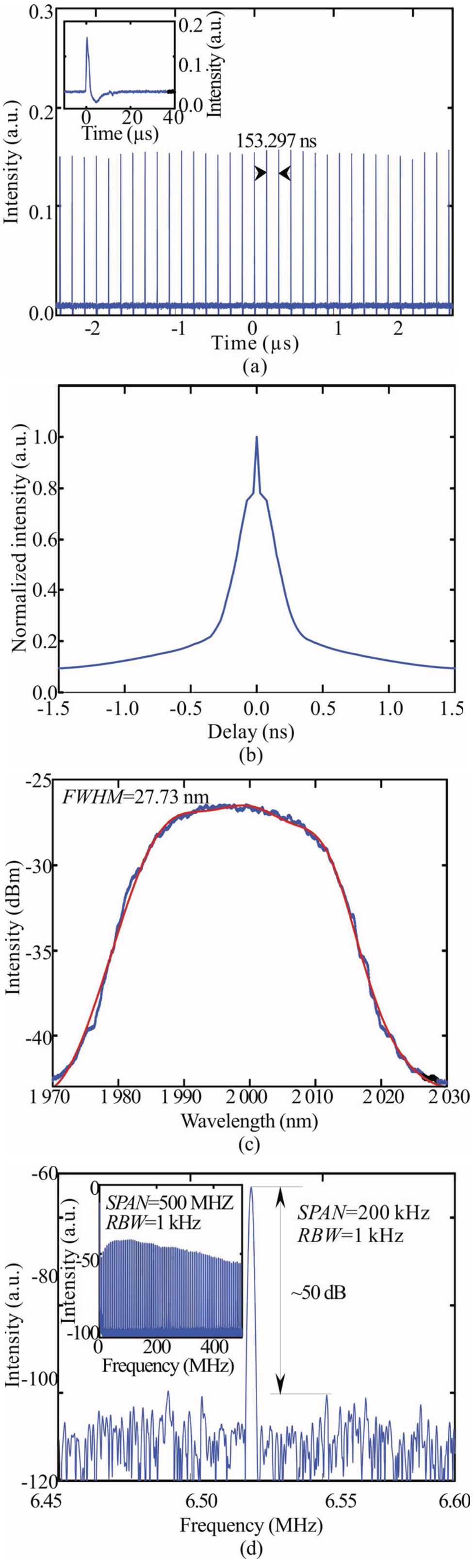


Fig.3 Experimental results of the NLML laser based on NOLM: (a) Oscilloscope trace; (b) The calculated autocorrelation trace; (c) Optical spectrum of the NLML laser; (d) RF spectrum with 1 kHz resolution (Inset is the RF spectrum of 500 MHz span.)

To evaluate the dynamic evolution of the pulse spectrum and pulse energy, we fixed the PCs and changed only pump power. As shown in Fig.4, it demonstrates the change in the corresponding pulse spectra. The intensity in the central region of pulse spectrum increases continuously while the *FWHM* broadens with the pump power. In addition, the optical spectrum of the mode-locking can be well fitted by the Gaussian profile. And it can be observed that our dual-NOLM fiber laser keeps operating in a noise-like state along well with increasing pump power, thus the emitted light is laser. Under NLML operation conditions, the pulse energy increases linearly with pump power, which is depicted in Fig.5. Note that the pulse energy increases linearly with the pump power without saturation. Thus, it is believed that the higher pulse energy in a wider range can be obtained by higher pump source.

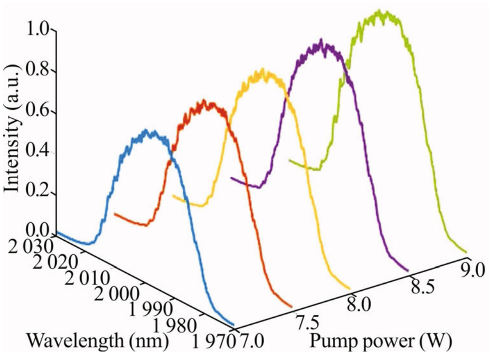


Fig.4 Pulse temporal profiles with the increasing pump power

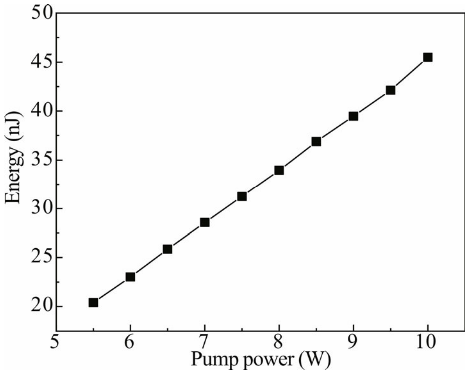


Fig.5 The pulse energy versus pump power

Herein, we experimentally demonstrated a Tm-doped fiber laser based on NOLM in this paper. The spectrum bandwidth, central wavelength, repetition rate and single pulse energy are 29.18 nm, 1 999.7 nm, 6.523 MHz, 46 nJ, respectively. To our knowledge, this is the first report of a Tm-doped NLML fiber laser based on dual-NOLM. This simple and inexpensive structure will reduce the cost and obtain relatively higher pulse energy simultaneously. Moreover, the NLML pulse is realized based on the dual-NOLM, while this designed fiber laser exhibits excellent output performance in comparison with others. Our results suggest that the NLML fiber laser is beneficial for applications in supercontinuum.

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