2.04 μm harmonic noise-like pulses generation from a mode-locked fiber laser based on nonlinear polarization rotation*

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We report the generation of harmonic noise-like mode-locked pulses in a thulium-doped fiber laser. In this laser, mode-locking can be realized through the nonlinear polarization rotation (NPR) technique. The ring cavity configuration uses 5 m of a Tm-doped dual-cladding fiber, as a gain medium, pumped by a 793 nm diode laser. The cavity uses a couple of polarization controllers (PCs) and polarization-dependent isolator to form a nonlinear polarization-rotating saturable absorber. By carefully adjusting of the PCs, the laser generates noise-like mode-locked pulses at the 2.04 μm band. With the increase of the pump power, the laser generates harmonics of the mode-locking fundamental repetition frequency of 6.88 MHz, from which we can obtain the second harmonic in a controlled mode. The obtained results may be useful for enhancing the understanding of the mechanism and characteristics of noise-like pulse at the 2 μm band.

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In recent years, passively mode-locked fiber lasers have attracted great interest due to their small size, simple structure and low cost[1,2]. In particular, the 2 μm fiber laser can produce the laser of eye safe band and atmospheric communication window, which are widely used in laser medical and space communication fields[3]. Different methods have been used for obtaining of passive mode-locked pulses in fiber lasers, such as nonlinear amplifying loop mirror (NALM), nonlinear polarization rotation (NPR) as artificial saturable absorbers, and graphene, topological insulators, black phosphorus as true saturable absorber. These lasers can realize various types of mode-locking pulses depending of the cavity structure, the pump power source and the adjustment of the polarization state in the cavity[4-6], making them attractive for specific applications in different research fields. These obtained pulses can exhibit different characteristics, such as traditional soliton[7-9], dissipative soliton[10,11], dissipative soliton resonance (DSR)[4,12-15], noise-like pulse (NLP)[3,5,16-18], among others. Particularly, high energy pulses can be generated by DSR and NLP. The DSR is a single pulse, which expands continuously with the increase of pump power and maintains constant amplitude. However, due to the strict requirements of the laser cavity, these are difficult to obtain such pulses. Relatively speaking, NLP is easier to obtain, such pulses are composed of many ultra-short pulses with wide and smooth optical spectrum, low time-domain coherence, and have important applications in the optical measurement, the optical sensing, the super-continuum spectrum and other fields[19]. However, NLP pulse energy will not increase infinitely like DSR pulse, and under certain conditions, the pulse will split, resulting in the phenomenon of harmonic mode-locked pulse[20-22]. Although noise-like mode-locking pulses have been reported, noise-like harmonic mode-locking pulses at 2 μm bands are rarely reported.

In this paper, we have adopted the passive mode locking principle of nonlinear effect of NPR structure with simple and stable and quick recovery time. And the dispersion management technology is used to make the NPR cavity average dispersion in near zero dispersion region. The noise-like pulse is obtained in 2 μm band with full width at half maximum (*FWHM*) of 24.3 nm. And further study the output characteristics of this noise-like pulse, the experiment result indicates that, when the pump power increases, by adjusting the state of the polarization controller in the cavity, the noise-like pulse will split and the harmonic noise-like pulse up to the 2nd harmonic can be obtained. The experimental results show that the 2nd harmonic noise-like pulse will produce pulse splitting under certain conditions, and the

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phenomenon of harmonic mode-locked pulse will help us better understand the essential characteristics of noise-like pulse and promote its popularization and application in production and life.

A simplified thulium doped all-fiber laser based on NPR is depicted in Fig.1. The laser adopts the structure design of ring cavity. The 793 nm semiconductor laser (BW-LD793-12S, China) with a maximum output power of 12 W provides pumping. The pumping light is introduced into the cavity by (2+1)×1 combiner. The single-mode dual-clad thulium doped fiber (IXF-2CF-Tm-O-10-130, IXFiber, France) with a length of about 5 m is the gain medium. Two extruded polarization controllers (PCs) and one polarization dependent isolator (PD-ISO) constitute the mode locking device of the compact NPR structure. The total cavity length of the fiber laser is about 30 m, which are composed of 5 m gain fiber (dispersion value: −0.070 7 ps^2/m), 15 m ordinary single-mode fiber (dispersion value: −0.067 9 ps^2/m) and 10 m dispersion compensation fiber UHNA7 (dispersion value: +0.13 ps^2/m). The net dispersion value in the cavity is about −0.002 8 ps^2, so the laser operates in a small anomalous dispersion region. In the anomalous region near the zero dispersion point, it is easier to stimulate the spectral broadening caused by the nonlinear effect[23]. The spectral width of noise-like mode-locked pulse is wider, and it is easy to appear under the above conditions.

The output coupler (OC) with a spectral ratio of 70/30 is adopted to realize the coupling output of the laser. The output terminal (30%) is connected to the optical spectrum analyzer (Omni-750i, China), spectrum analyzer (FSL3, Rohde & Schwarz, Germany), oscilloscope (Wave Runner 610Zi, USA), photo-detector (ET-5000F, EOT, USA) and optical power meter (Vega P/N 7Z01560, OPHIR, Israel), in order to measure the optical spectrum, radio frequency (RF) spectrum, time domain waveform and output power of the mode-locked pulse.

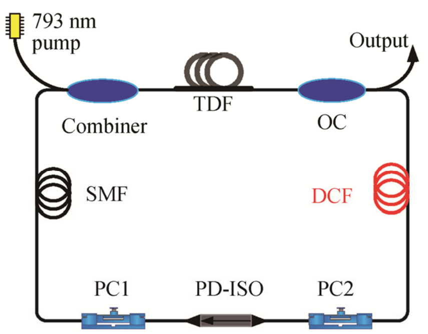

Fig.1 Experimental setup of the harmonic noise-like mode-locked Tm-doped fiber laser

As shown in Fig.2, the output characteristic of Tm -doped fiber laser (TDFL) is investigated by changing the pump power in a wide range. The laser output power increases linearly with the launched pump power after meeting the threshold. As the launched power reaches the threshold, TDFL operates in three regimes including continuous wave (CW: 2.5—3.5 W), noise-like mode-locking (NLML: 3.6—5.8 W) and harmonic noise-like mode-locking (HNLML: 5.9—7.0 W). The reason for the mode locking threshold is very high is that the dispersion compensation fiber core is very fine and the welding has a great loss. When the state of the PC in the laser cavity is carefully adjusted in the experiment, it is found that the NLP will split and output the harmonic noise-like mode-locked pulse. Additionally, harmonics of higher orders can also be obtained, but with arbitrarily changes without adequate control over them.

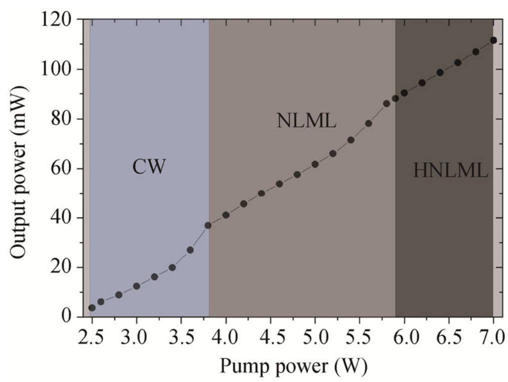

Fig.2 Average output power under different pump power conditions

As the launched pump power increases to the threshold, stable NLML can be obtained by adjusting the PCs. To achieve better mode locking, we continue to increase the pump power to 4.0 W and observe the optical spectral and the time domain characteristics. In the process of increasing the pump, the fiber laser can always maintain the mode locking state. Fig.3 shows the fundamental frequency mode-locking optical spectrum, pulse diagram, the fitting autocorrelation trace and RF spectrum when the pump power is 4.0 W. It can be seen that the central wavelength of the mode-locked pulse is 2 048.4 nm and the *FWHM* is 24.3 nm, and it has a smooth spectral shape, as shown in Fig.3(a). This is a typical feature of noise-like mode-locking pulses. Fig.3(b) is the pulse sequence detected by an oscilloscope. At this time, the pulse repetition frequency is 6.88 MHz, which is the fundamental frequency pulse of the laser. Fig.3(c) shows that the fitting autocorrelation trace of the output pulses contains a narrow spike on a broad pedestal indicating the NLML operation[16-22]. Further study on the stability of mode locking, and the measured RF spectrum is shown in Fig.3(d). Fig.3(d) demonstrates the RF spectrum at a scanning range 1.5 MHz with a resolution of 1 kHz. The measured repetition rate of 6.88 MHz matches well with the cavity length. In Fig.3(d), the signal to noise ratio (*SNR*) is ~43 dB indicating the inherent jittering of the NLML operation.

Generally speaking, the higher pump power, the more likely the mode locked pulse in the fiber laser will split. When the pump power level exceeds the 5.9 W value, the mode-locked laser generates harmonic pulses of the fundamental repetition frequency. Notably, when the noise-like pulse harmonic mode locked occurs, the optical spectral shape is similar to the optical spectral of the fundamental frequency pulse, as shown second harmonic optical spectrum in Fig.4(a). Moreover, when the harmonic noise pulses appear, there is no relative motion or obvious interaction between the pulses[21]. And Fig.4(b) also shows that the fitting autocorrelation trace of the output pulses contains a narrow spike on a broad pedestal indicating the HNLML operation[20-22].

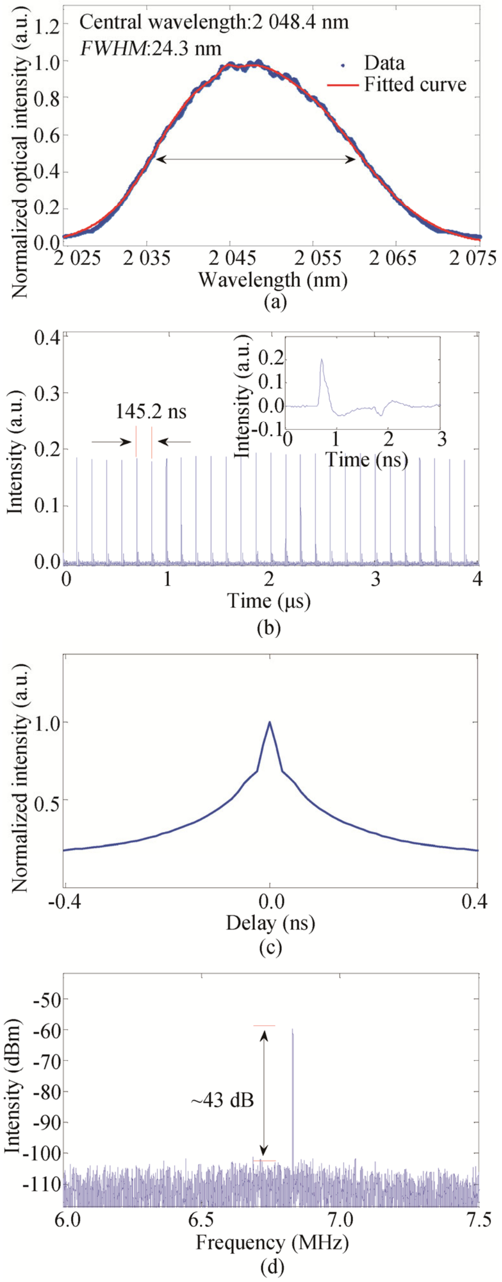

Fig.3 Experimental results of NLML laser based on NPR resonator: (a) Optical spectrum; (b) Oscilloscope trace; (c) The calculated autocorrelation trace; (d) RF spectrum

In the experiment the second harmonic is obtained in a stable and controlled mode, this is displayed in Fig.5(a). To verify the presence of harmonics, Fig.5(b) displays the RF spectra of the obtained harmonics, which are congruent with the repetition rate corresponding to the pulse trains observed in Fig.5(a). By fine-tuning the PCs, the second harmonic operation can evolve into an intermediate state that can be controlled and cannot be controlled, and these pulses are not evenly distributed as show Fig.6, the Ref.[24] has a similar phenomenon. In addition, the study on the chirp characteristics of the harmonic mode-locked pulse is helpful to quantitatively study the spectral broadening mechanism of the mode-locked pulse. However, due to the limitation of the measurement accuracy of the 2 μm band autocorrelation instrument and spectrometer in the laboratory, this part is not analyzed in depth. Moreover, harmonics of higher orders are also obtained, but with discretionarily changes without adequate control over them. It can be seen that the mode-locked pulse becomes more and more unstable as the number of harmonics increases.

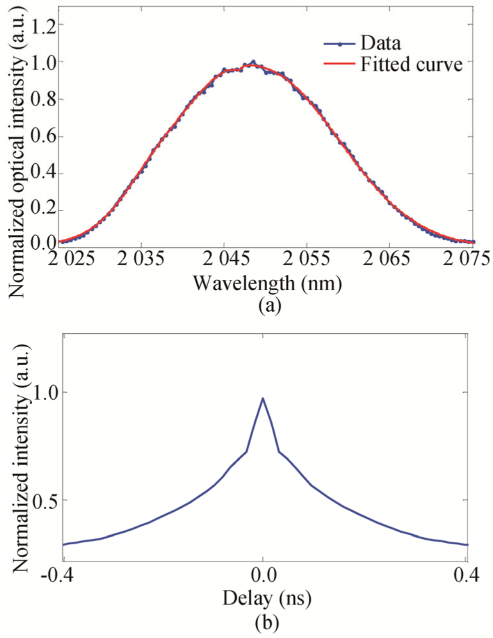

Fig.4 (a) Optical spectrum of the harmonic mode locking operation; (b) The calculated autocorrelation trace

In this work, the generation of stable harmonic noise-like pulses through a passively mode-locked Tm-doped fiber laser fiber laser in near zero dispersion region and NPR configuration are experimentally demonstrated. The results obtained, such as the optical spectrum, the temporal profile, the autocorrelation trace and the RF spectrum confirm that these are pulses that belong to the NLP regime. The range of pumping for this experimental arrangement goes from a lase threshold of 0 W to a maximum of 7.0 W to avoid damage to the optical components of the laser. Above of 5.9 W of pumping, harmonic pulses of the fundamental repetition rate appear and it is possible to obtain until the second harmonic in a controlled mode. Further, an intermediate

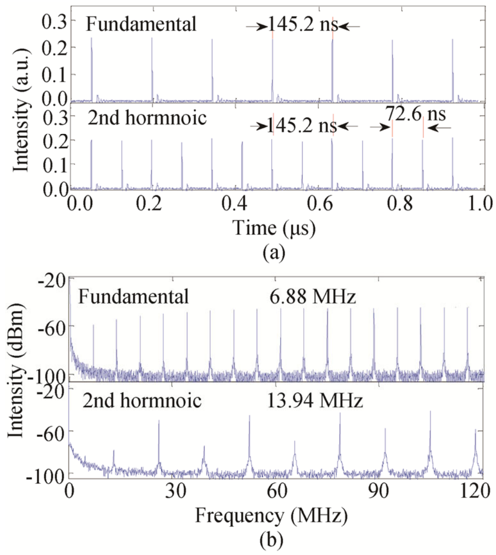

Fig.5 (a) Trains of the fundamental and second harmonic pulses in the time domain; (b) RF spectra of the fundamental and second harmonics obtained in span 120 MHz

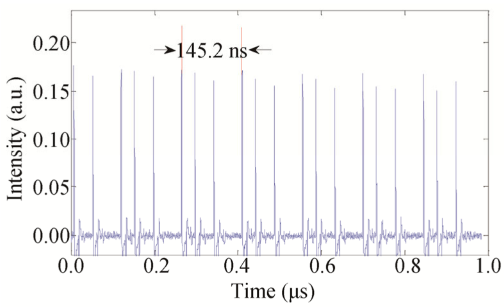

Fig.6 The harmonics further split into uneven mode-locking pulses

state can also be obtained, and the pulses are not evenly distributed. Nevertheless, the mode-locked pulse becomes more and more unstable as higher order harmonics are obtained. The experimental results are helpful to further understand the mechanism and characteristics of 2 μm noise mode-locked pulses.

References

[1] Zhao Xiao-li, Luo Fei, Zhang Yu-min, Meng Fan-yong and Dong Ming-li, Optoelectronics Letters **15**, 122 (2019).

[2] Zhao Feng-yan, Wang Yi-shan, Wang Hu-shan, Yan Zhi-jun, Hu Xiao-hong, Zhang Wei, Zhang Ting and Zhou Kai-ming, Scientific Reports **8**, 16369 (2018).

[3] Grzegorz Sobon, Jaroslaw Sotor, Aleksandra Przewolka, Iwona Pasternak and Krzysztof Abramski, Optical Express **24**, 20359 (2016).

[4] Georges Semaan, Alioune Niang, Mohamed Salhi and François Sanchez, Laser Physics Letters **14**, 055401 (2017).

[5] Jesús Pablo Lauterio-Cruz, Juan Carlos Hernandez-Garcia, Olivier Pottiez, Julián Moisés Estudillo-Ayala, E. A. Kuzin, Roberto Rojas-Laguna, Héctor Santiago-Hernández and Héctor Santiago-Hernández, Optical Express **24**, 13778 (2016).

[6] Deng Zhuo-Shuang, Zhao Guan-Kai, Yuan Jia-Qi, Lin Jin-Ping, Chen Hong-Jie and Liu Hong-Zhan, Optical Letters **42**, 4517 (2017).

[7] Lynn E Nelson, D. J. Jones, K. Tamura, H. Haus and E. P. Ippen, Applied Physics B **65**, 277 (1997).

[8] Xu Jia, Wu Si-da, Liu Jiang, Sun Ruo-yu and Wang Pu, Chinese Journal of Lasers **40**, 0702033 (2013). (in Chinese)

[9] Liu Peng, Wang Tian-shu and Zhang Peng, Acta Photonica Sinica **45**, 06140003 (2016). (in Chinese)

[10] Liu Xue-ming, Optical Express **17**, 22401 (2009).

[11] Zhang Xin, Hu Ming-lie, Song You-jian and Wang Qing-yue, Acta Physica Sinica **59**, 1863 (2010). (in Chinese)

[12] Wu Xiao-hua, Tang Ding-yuan, Zhang Hua and Zhao Lu-ming, Optical Express **17**, 5580 (2009).

[13] Duan Li-na, Liu Xue-ming, Mao Dong, Wang Lei-ran and Wang Guo-xi, Optical Express **20**, 265 (2012).

[14] Zhao Kang-jun, Wang Pan, Ding Yi-Hang, Yao Shun-yu, Gui Li-li, Xiao Xiao-sheng and Yang Chang-xi, Applied Physics Express **12**, 012002 (2018).

[15] Wu Yun-feng, Tian Jin-rong, Dong Zhi-kai, Liang Cheng-bin and Song Yan-rong, IEEE Photonics Journal **11**, 1 (2019).

[16] Liu Jun, Chen Yu, Tang Ping-hua, Xu Chang-wei, Zhao Chu-jun, Zhang Han and Wen Shuang-chun, Optical Express **23**, 6418 (2015).

[17] Zhou Xin-wu, Cheng Zhao-chen, Shi Yu-hang, Guo Hao-dong and Wang Pu, IEEE Photonics Technology Letters **30**, 985 (2018).

[18] Gao Jin-juan, Zhou Yong, Liu Yan-jun, Han Xi-le, Guo Quan-xin, Lu Zheng-yi, Guo Lin-guang, Shang Xin-xin, Yang Wen-qing, Niu Kang-di, Na Ming, Wang Zhi-hao, Zhang Hua-nan and Jiang Shou-zhen, Applied Optics **58**, 6007 (2019).

[19] Lin Shih-shian, Hwang Sheng-kwang and Liu Jia-ming, Optical Express **22**, 4152 (2014).

[20] Olivier Pottiez, Juan Carlos Hernandez-Garcia, Baldemar Ibarra-Escamilla. E. A. Kuzin, M. Durán-Sánchez and Andrés González García, Laser Physics **24**, 115103 (2014).

[21] Luo Zhi-chao, Zheng Xu-wu, Luo Ai-ping and Hu Wen-cheng, Applied Physics **4**, 107 (2014).

[22] Edgar Bravo Huerta, M. Durán-Sánchez, Baldemar Ibarra-Escamilla, Ricardo Iván Álvarez-Tamayo, Héctor Santiago-Hernández, Miguel Bello-Jiménez and Evgeny A. Kuzin, SPIE **10897**, 108971Y (2019).

[23] Hu Jian and Zhang Xian-ming, Chinese Journal of Quantum Electronics **33**, 292 (2016). (in Chinese)

[24] Liang Hu, Liu Yan-ge, He Rui-jing, Li Hong-ye and Wang Zhi, IEEE Photonics Technology Letters **30**, 2009 (2018).