Passively synchronized Q-switched and simultaneous mode-locked dual-band Tm^{3+}:ZBLAN fiber laser at 1.48- and 1.85-µm using common graphene saturable absorber

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Abstract: We demonstrate a dual-band Tm^{3+}:ZBLAN fiber ring laser with synchronized Q-switched pulses and a dual-band simultaneous mode-locked Tm^{3+}:ZBLAN fiber linear laser at 1.48 µm and 1.85 µm using a common graphene saturable absorber.

OCIS codes: (060.2390) Fiber optics, infrared; (140.3540) Lasers, Q-switched; (140.4050) Mode-locked lasers

1. Introduction

Thulium-doped (Tm^{3+}) ZBLAN fiber is an excellent rare-earth-doped active fiber for two important electronic transitions of $^3H_4 \rightarrow {}^3F_4$ and $^3F_4 \rightarrow {}^3H_6$ with emissions at ~1480 nm and ~1900 nm respectively, owing to its unique properties such as low phonon energy and low transmission loss over a broad wavelength range [1]. Laser sources at a wavelength of 1480 nm are situated in the S-band of the third transmission window and function as ideal pump sources for erbium-doped fiber amplifiers (EDFAs) and Raman fiber amplifiers, while laser sources at a wavelength of 1900 nm are situated in the newly exploited fiber transmission window (1850~2100 nm) [2] with widespread applications in mid-infrared pump sources and chemical sensing.

Passive dual-band pulsed fiber lasers based on a common graphene saturable absorber (SA) are of great significance in nonlinear frequency conversion and Raman scattering spectroscopy due to advantages such as compactness, environmental robustness, and flexibility. Previously, the use of a common graphene SA to synchronize two passively Q-switched silica fiber lasers, one emitting at 1060 nm based on Yb-doped fiber and the other at 1530 nm based on Er:Yb co-doped fiber, was reported by Wu *et al.* [3], while simultaneous mode-locking at 1565 nm with Er-doped fiber and 1944 nm with Tm-doped fiber was obtained by Sotor *et al.* [4].

In this paper, we demonstrate for the first time the use of a common graphene SA to obtain (1) a passively synchronized Q-switched Tm^{3+}:ZBLAN fiber ring laser at 1480 nm and 1850 nm and (2) a simultaneous mode-locked Tm^{3+}:ZBLAN fiber laser at 1480 nm and 1870 nm. Compared with previous studies, our scheme significantly simplifies the implementation with the use of a single gain medium (Tm^{3+}:ZBLAN fiber) to achieve dual-band Q-switched and mode-locked operation around 1480 nm and 1850 nm. Such a system laser can find applications in multi-wavelength cavity ring-down spectroscopy and allow for transmitters for optical communications in the S-band and around 2 µm.

2. Passive Q−switched pulse synchronization of Tm^{3+}:ZBLAN fiber laser at 1480 nm and 1850 nm

Fig. 1(a) shows the schematic of passively synchronized Q-switched Tm^{3+}:ZBLAN fiber laser. It consists of two ring cavities with one common branch including graphene SA. The gain fiber for lasing operation at 1480 nm (top loop) is an 80 cm length of Tm^{3+}:ZBLAN fiber, whereas the gain fiber for lasing operation at 1850 nm (bottom loop) is a 35 cm length of the same fiber [5]. The Tm^{3+}:ZBLAN fiber is coupled with SMF-28 fiber based devices through mechanical splices (represented by × in Fig. 1(a)), inducing ~2 dB loss per pair. In the top ring cavity, the 1480 nm loop is pumped by a 1064 nm Yb-doped fiber laser (P_{1064}) via a 1064/1480 nm wavelength division multiplexer (WDM). A 1480 nm polarization independent isolator (PI-ISO) ensures the 1480 nm signal to propagate clockwise. In the bottom ring cavity, the 1850 nm loop is pumped by a 1560 nm Er-doped fiber laser (P_{1560}) via a 1560/1850 nm WDM. An 1850 nm PI-ISO ensures the 1850 nm signal to propagate counter-clockwise. Two optical couplers with a splitting ratio of 90/10 are used to extract the laser output from the two ring cavities (10% as the output ports). Two polarization controllers (PCs) are used to adjust intra-cavity polarization and to optimize laser output in each cavity. Both signals are combined and separated back via two 1480/1850 nm WDMs. The graphene film is deposited and sandwiched between two fiber connectors to form the SA [6].

Pulse synchronization behaviors are observed when both cavities operate together. The cavity with a higher repetition rate dominates the other cavity. For example, we set P_{1560} = 1020 mW to make the 1850 nm loop produce ~20 kHz pulses, and then characterize the 1480 nm loop. CW lasing at 1480 nm starts at a lower threshold due to the change of graphene transmission loss. As P_{1064} increases from 526 mW to 574 mW, Q-switched pulses at 1480 nm are observed with a fixed repetition rate of ~20 kHz. During this process, these two cavities both produce ~20 kHz Q-switched pulses. As P_{1064} increases further up to 682 mW, repetition rates of Q-switched pulses at 1480 nm and 1850 nm both simultaneously increase from 20 kHz to 40.5 kHz, indicating pulses from the 1850 nm loop follows the repetition rate of the 1480 nm loop. Similar pulse synchronization in the 1850 nm loop are also achieved as shown in Fig. 2(b). An optical coupler is used to combine outputs from two cavities in order to observe the synchronized pulse performance. When P_{1064} = 574 mW and P_{1560} = 1020 mW, the combined optical spectrum and synchronized Q-switched pulse trains in the time domain are depicted in Figs. 1(b) and (c), showing the ultra-broadband operation of graphene.

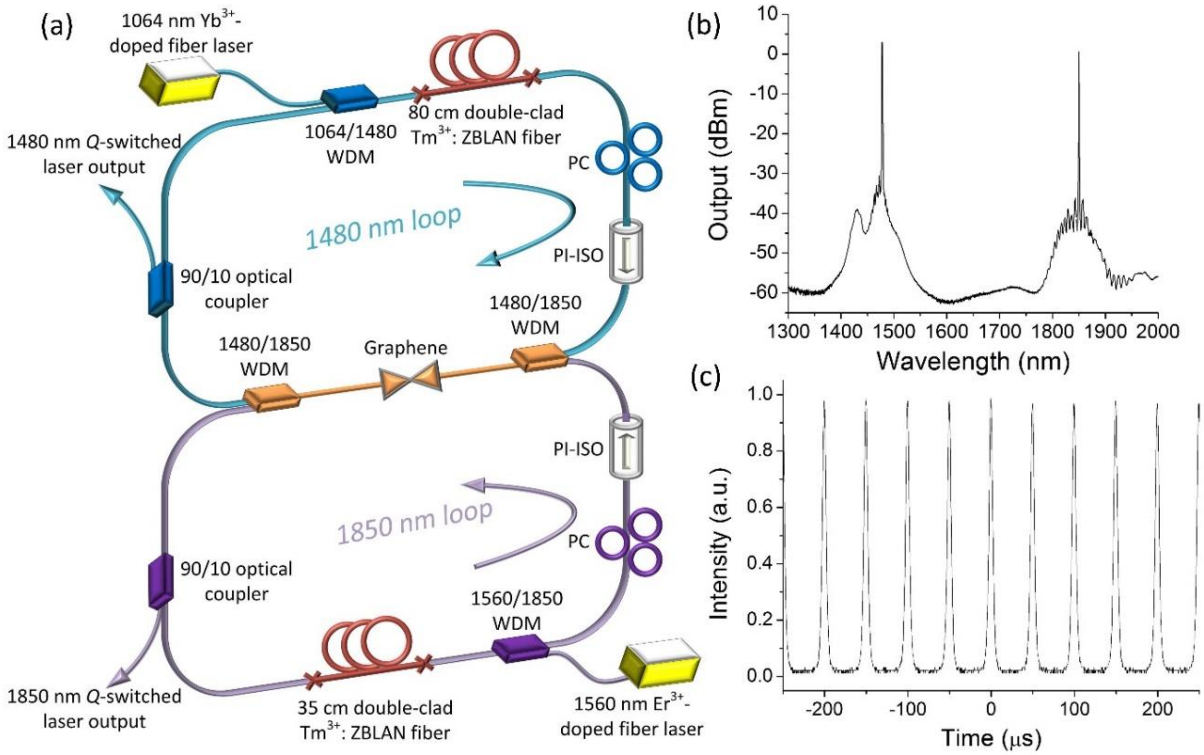

Fig. 1. (a) Experimental setup of the passively synchronized Q-switched Tm^{3+}:ZBLAN fiber laser; (b) combined optical spectrum and (c) synchronized Q-switched pulse trains when P_{1064} = 574 mW and P_{1560} = 1020 mW.

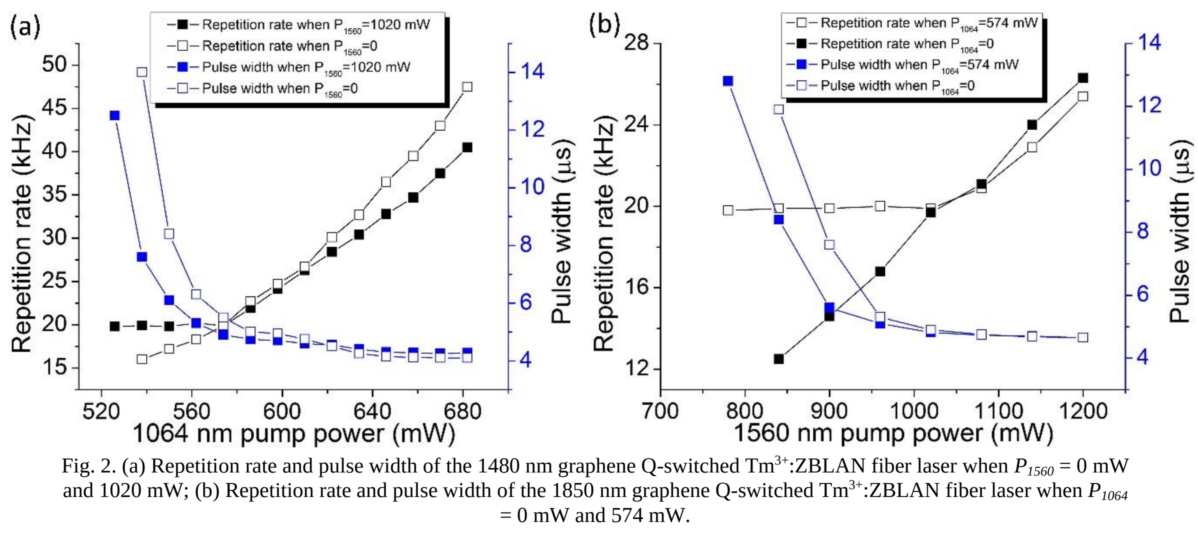

Fig. 2. (a) Repetition rate and pulse width of the 1480 nm graphene Q-switched Tm^{3+}:ZBLAN fiber laser when P_{1560} = 0 mW and 1020 mW; (b) Repetition rate and pulse width of the 1850 nm graphene Q-switched Tm^{3+}:ZBLAN fiber laser when P_{1064} = 0 mW and 574 mW.

3. Simultaneous mode-locked Tm^{3+}:ZBLAN fiber laser at 1480 nm and 1870 nm

In order to improve the output efficiency and initiate dual-band mode-locking, two linear cavities with shorter cavity lengths and one shared branch are adopted, as shown in Fig. 3(a). This laser consists of two independent linear cavities for lasing operations at 1480 nm and 1850 nm, respectively, along with one common branch including the graphene SA and one output coupler. The same gain fiber and lengths used for the previous dual-band Q-switched laser are used again for the 1480 nm and 1850 nm branches, respectively. Two gold-tipped mirrors serve as two reflectors to form one end of each cavity and two circulators designed for operation at 1480 nm or 1850 nm are used to ensure unidirectional propagation and to allow for light oscillation in each linear cavity.

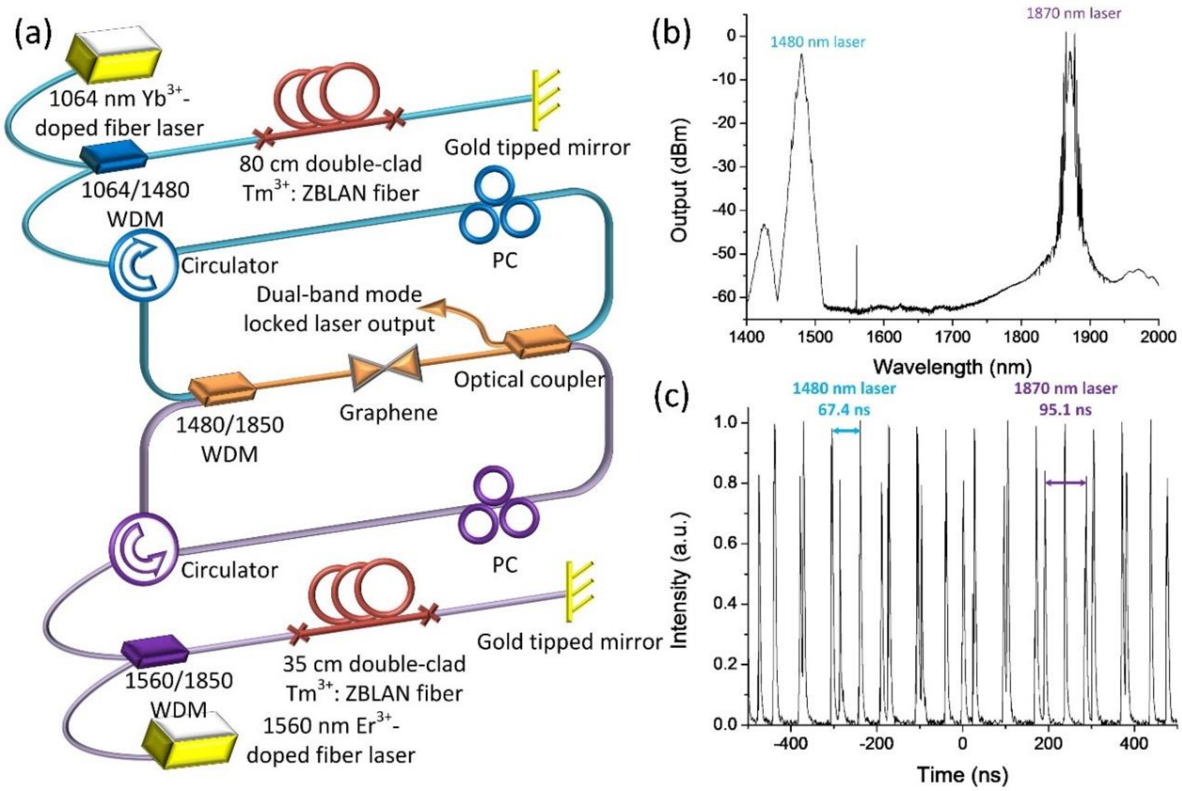

Fig. 3. (a) Experimental setup of the simultaneous mode-locked Tm^{3+}:ZBLAN fiber laser; (b) optical spectrum and (c) mode-locked pulse trains when P_{1064} = 694 mW and P_{1560} = 1320 mW.

Fig. 3(b) shows the full optical spectrum in a 600-nm span, demonstrating the ultra-broadband mode-locked operation at 1480 nm and 1870 nm simultaneously. The dispersions of both branches are both anomalous, indicating this fiber laser generates soliton-like pulses, which are also confirmed by the characteristic Kelly sidebands. These generated optical solitons have spectral widths of 4.12 nm and 3.78 nm for the 1480 nm and 1870 nm branches, respectively. Fig. 3(c) shows the temporal pulse trains for simultaneous mode-locked operation. Both branches operate with different repetition frequencies (14.95 MHz for 1480 nm and 10.48 MHz for 1870 nm), corresponding to their cavity lengths of ~13.4 m and ~19.1 m, respectively.

4. Conclusion

We have demonstrated the use of a common graphene SA to obtain (1) a passively synchronized Q-switched Tm^{3+}:ZBLAN fiber laser at 1480 nm and 1850 nm and (2) a simultaneous mode-locked Tm^{3+}:ZBLAN fiber laser at 1480 nm and 1870 nm at repetition frequencies of 14.95 MHz and 10.48 MHz, respectively. The dual-band Q-switched pulses will enable multi-wavelength cavity ring-down spectroscopy while the dual-band mode-locked pulses will allow for making transmitters for optical communications, along with supercontinuum generation in the S-band and around 2 μm.

5. References

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