Graphene-based passively *Q*-switched Tm^{3+}:ZBLAN fiber laser at 1480 nm

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***Abstract*—We demonstrate for the first time a graphene-based passively *Q*-switched Tm^{3+}:ZBLAN all-fiber laser at 1480 nm. Pulses with a duration of ~ 9 μs, repetition rate of 29.9 kHz, and energy up to 447.16 nJ are obtained.**

I. Introduction

ZrF_4-BaF_2-LaF_3-AlF_3-NaF (ZBLAN) is an excellent host for rare-earth ions and has become an important material for fiber lasers due to its low phonon energy and long radiative lifetime [1]. Tm-doped (Tm^{3+}) ZBLAN fibers provide a variety of energy transitions to develop fiber lasers operating at a wide range of wavelengths. Especially the $^3H_4 \rightarrow {}^3F_4$ transition with a resulting photon wavelength of ~1480 nm, is of great importance for S-band fiber communication and chemical detection [2, 3].

Q-switched fiber lasers have attracted considerable attention due to their widespread applications in fiber sensing, reflectometry, medicine and telecommunications. Compared with actively *Q*-switched fiber lasers, passively *Q*-switched fiber lasers provide the advantages of low cost, simplicity and compactness. Recently, graphene has attracted considerable interest as a saturable absorber (SA) to develop passively *Q*-switched fiber lasers due to its unique properties of low saturation intensity, ultrabroad operating wavelength range and ease of fabrication [4]. Graphene-based passively *Q*-switched ZBLAN fiber lasers have been demonstrated at 1190 nm and 3 μm by Ho^{3+}-doped ZBLAN fiber [5, 6] and at 2.78 μm by Er^{3+}-doped ZBLAN fiber [7]. There have been no reports, however, of graphene-based *Q*-switched Tm^{3+}: ZBLAN fiber lasers.

In this paper, we demonstrate for the first time a passively *Q*-switched Tm^{3+}:ZBLAN all-fiber laser at 1480 nm based on a graphene SA. Stable Q-switched lasing operation starts at a pump power of 426 mW and pulses with a duration of ~9 μs, repetition rate varying from from 16.9 kHz to 29.9 kHz, and pulse energies up to 447.16 nJ are obtained.

II. Experimental Setup

Fig. 1 shows a schematic of the graphene-based passively *Q*-switched Tm^{3+}:ZBLAN fiber laser. We use 85 cm of double-clad Tm^{3+}:ZBLAN fiber as the gain medium, which is pumped by a 1064 nm Yb-doped fiber laser (P_{1064}) via a 1064/1480 nm wavelength division multiplexer (WDM). Manufactured by IRphotonics/Thorlabs Inc., the Tm^{3+}:ZBLAN fiber is doped with 8,000 ppm Tm^{3+}, has a core diameter of 8 μm, a cladding diameter of 125 μm, and a numerical aperture (NA) of 0.13 [3]. The Tm^{3+}:ZBLAN fiber is coupled to SMF-28 fiber-based components through a pair of mechanical splices (represented by X in Fig. 1). A polarization controller (PC) is used to optimize the laser output and a polarization independent isolator is used to ensure the unidirectional propagation in the laser cavity. Between the PC and the isolator, a graphene film is deposited and sandwiched between two fiber connectors to form the SA [8]. A coupler with a splitting ratio of 50:50 is used to extract the laser output. The total cavity length of the *Q*-switched all-fiber laser is ~10.5 m. The total estimated cavity loss is ~13.5 dB, which includes ~4 dB loss from the graphene SA, ~2 dB loss from mechanical splices, ~2 dB insertion loss, ~0.5 dB loss from the isolator, and 5 dB loss from the WDM and 3 dB couplers. The optical spectrum is measured by an optical spectrum analyzer (YOKOGAWA AQ6375) with a resolution bandwidth of 0.05 nm while the temporal characteristics are monitored by a combination of a 7 GHz photodetector (Newport, 818-BB-51F) and a 60 MHz oscilloscope (Agilent, 54621A). The output power is measured by a power meter (EXFO, FPM-300).

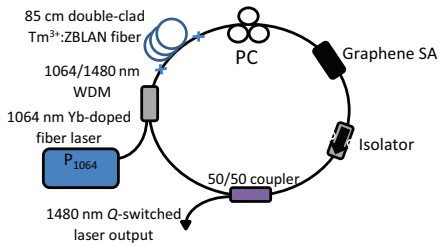

Fig. 1. Graphene-based *Q*-switched Tm^{3+}:ZBLAN fiber laser configuration.

III. Results and Discussion

In our experiment, continuous wave (CW) lasing starts at a pump power of ~390 mW. Stable *Q*-switched pulses are then established when the pump power is increased to ~426 mW and is maintained up to ~527 mW. Note that all the pump power values are measured after 1064/1480 nm WDM. The *Q*-switched pulse trains observed on the oscilloscope are very stable. Fig. 2 shows a typical optical spectrum of the *Q*-switched fiber laser output when the pump power is 502.8 mW. The central wavelength is 1481.37 nm and the full-width at half-maximum (FWHM) bandwidth is ~0.08nm.

Two typical *Q*-switched pulse trains at pump powers of 446.6 mW and 502.8 mW are shown in Figs. 3(a) and 3(b), respectively. From the pulse trains, we can observe that there is no amplitude modulation in each pulse, which suggests the absence of self-mode-locking. Fig. 3(c) shows a single pulse envelope with a pulse duration of 8.62 μs at a pump power of 502.8 mW. Fig. 4 shows the pulse repetition rate and the pulse

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duration measured at different pump powers. As the pump power increases from 426 mW to 527 mW, the repetition rate (black dots) increases linearly from 16.9 kHz to 29.9 kHz at a rate of 0.129 kHz/mW, a typical signature of *Q*-switching. On the other hand, the pulse duration (red squares) decreases from 12.25 μs to 8.25 μs and then increases to 8.9 μs. At a lower pump power (< 460 mW), the pulse duration drops exponentially; while at a higher pump power (> 470 mW), the pulse duration keeps a level of ~8.5 μs and increases a little bit, indicating the graphene SA is almost saturated.

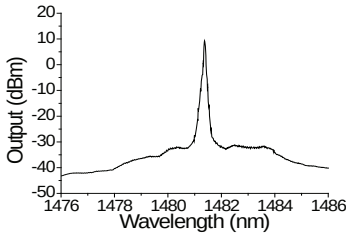

Fig. 2. Optical output spectrum of the graphene *Q*-switched Tm^{3+}:ZBLAN fiber laser when P_{1064} = 502.8 mW.

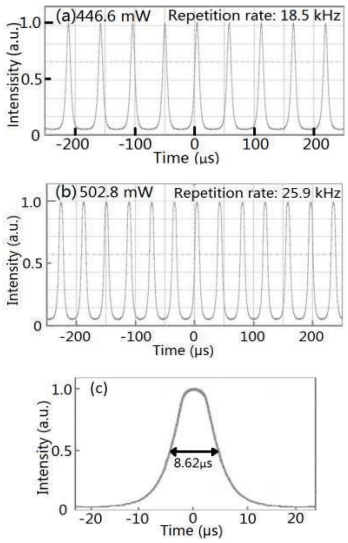

Fig. 3. (a) *Q*-switched pulse trains when P_{1064} = 446.6 mW; (b) *Q*-switched pulse trains and (c) single pulse envelope when P_{1064} = 502.8 mW.

The measured average output power (black dots) and the calculated pulse energy (red squares) as a function of the pump power are shown in Fig. 5. The average output power increases linearly with a slope efficiency of 9.77%, while the pulse energy keeps a saturated power level of ~450 nJ at high pump powers due to the bleaching effect of graphene SA itself. At the pump power of 527 mW, the average output power is 13.37 mW, and the calculated pulse energy and peak power are 447.16 nJ and 47.2 mW, respectively. The peak power could be further improved by shortening the cavity length to decrease the pulse duration, along with evanescent field interaction with SAs [9] to avoid damaging the graphene.

IV. SUMMARY

We have demonstrated a graphene-based *Q*-switched Tm^{3+}:ZBLAN all-fiber laser at an operating wavelength of 1480 nm with a repetition rate range from 16.9 kHz to 29.9 kHz. The threshold of stable *Q*-switched lasing operation is 426 mW. At a pump power of 527 mW, stable *Q*-switched pulses with pulse duration of 8.9 μs, and pulse energy of 447.16 nJ are obtained. In this experiment, no mode-locked operation of the Tm^{3+}:ZBLAN fiber laser is observed. Such a graphene Q-switched Tm^{3+}:ZBLAN fiber laser could become a low-cost and convenient light source for telecommunication, fiber sensing and chemical detection.

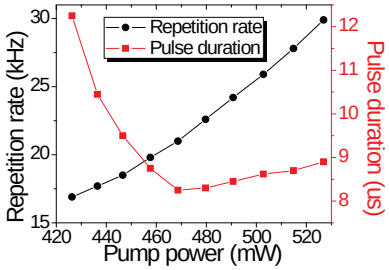

Fig. 4. Repetition rate (black dots) and pulse duration (red squares) of the graphene *Q*-switched Tm^{3+}:ZBLAN fiber laser as a function of pump power.

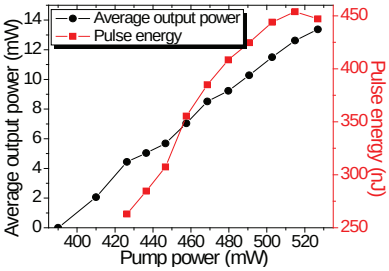

Fig. 5. Average output power (black dots) and pulse energy (red squares) of the graphene *Q*-switched Tm^{3+}:ZBLAN fiber laser as a function of pump power.

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