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High-power thulium fiber laser *Q* switched with single-layer graphene

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We report high-power 2 μm Tm^{3+} fiber lasers passively *Q* switched by double-piece single-layer graphene transferred onto a glass plate. Through manipulating intracavity laser beam size and increasing pump ratios, an average power of 5.2 W is directly achieved from the laser oscillator with an optical-to-optical slope efficiency of 26%. The laser pulse energy can be as high as $\sim 18 \mu\text{J}$, comparable to that from actively *Q*-switched fiber lasers. The narrowest pulse width is 320 ns, and the pulse repetition rate can be tuned from tens of kilohertz to 280 kHz by changing the pump power. To the best of our knowledge, this is the highest average power and pulse energy, as well as the narrowest pulse width, from graphene-based *Q*-switched 2 μm fiber lasers. © 2014 Optical Society of America

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Tm^{3+} -doped fiber lasers (TDFLs) at 2 μm have attracted much attention and have been the subject of extensive research in recent years due to their wide applications in remote sensing, medical surgery, industrial machining, and scientific experiments [1,2]. Rapid development of high-power 790 nm laser diodes (LDs) and high-quality double-clad Tm^{3+} fiber has made continuous wave (CW) output power of $\sim 2 \mu\text{m}$ fiber lasers surpass 1 kW [3]. However, many applications, such as laser radar and machining, require high-peak-power and/or high-energy pulsed 2 μm laser beams, which can be generally obtained from TDFLs using *Q*-switching [4] or mode-locking [5,6] methods. Whereas an acousto-optic modulated *Q*-switched 2 μm TDFL has achieved tens of watts of average power [7], the use of bulk modulating elements increases not only complexity but also cost of the fiber laser. Gain-switched TDFLs have also produced high-energy [8,9] or high average power [10] 2 μm laser pulses, but these systems usually need complex (expensive) solid-state lasers as the gain modulator, and most output pulses lack adequate stability. Resonant-pumped gain switching TDFL can provide stable 2 μm pulsing operation, but the average power was rather low (milliwatt levels) [11].

Passive mode locking and *Q* switching with semiconductor saturable absorbers (SAs) are usually used [12–14] to simplify the structure of 2 μm TDFLs. However, semiconductor SAs have some drawbacks, including a complex design for improving damage threshold [15], a narrow working wavelength range, and a relatively high cost. Recently, graphene (a monolayer of two-dimensional carbon atoms in a honeycomb structure) has attracted much attention and has been extensively used for mode locking or *Q* switching TDFLs [16–19]. Compared with other SAs, graphene SAs have many advantages, including large absorption per layer [20], wide operation spectral range [21], saturable absorption under strong optical excitation [22], moderate damage threshold, and ultrafast recovery

time [23,24]. However, the pulse energy and average power of mode-locked [16,17] or *Q*-switched [18,19] 2 μm TDFLs are comparatively low. This makes these passively modulated lasers hard to be used directly, and will lead to a complex (multiple stages) system structure even when they are used as the seed for a master oscillator power amplifier (MOPA) system. In addition, the pulse width in passively modulated fiber lasers is difficult to narrow when high-power output is pursued, which is restricted by the long fibers used.

In this Letter, we report high-power 2 μm Tm^{3+} fiber lasers *Q* switched with double-piece single-layer graphene (SLG) through manipulating the intracavity laser beam size and improving pump ratios (the ratio of pump power to the threshold pump). Double-clad Tm^{3+} fibers are adopted as the gain medium to improve the pump ratio and a collimating lens is used to increase the laser beam size incident on the graphene layers, greatly increasing the power damage threshold of graphene. In addition, we adopt a short fiber length combined with a large modulation depth of the double-piece SLG to shorten the pulse width in *Q*-switching operation. With these designs, a maximum output power of 5.2 W stable *Q*-switched 2 μm TDFLs are realized with pulse energy of up to 18 μJ . The pulse width can be narrowed to 320 ns. This kind of high average power and high pulse energy fiber laser in the 2 μm spectral range can be directly used in many applications and will greatly simplify the MOPA structure when used as the seed laser.

The SLG (two films of $\sim 20 \text{ mm} \times 20 \text{ mm}$) was chemical-vapor-deposition grown graphene and the films were separately transferred onto each side of a microscope cover glass plate (soda-lime glass) by a modified transfer process as described in detail in [25]. After transfer, the graphene on the glass plate was detected by Raman spectroscopy (WITec CRM 200 Raman system, 532 nm) and absorption microscopy. A representative Raman spectrum of the transferred sample is shown in Fig. 1(a). The

Fig. 1. (a) Raman spectrum of the graphene on the glass plate and (b) transmittance of the bare glass plate and the glass plate coated with SLG on both sides.

2D peak has a single sharp Lorentzian shape, clearly showing the signature of the SLG [26]. The D peak is very weak, indicating negligible defects [27] on the graphene sheet. The transmittance of the SLG on glass is shown in Fig. 1(b). During a large spectral range (from 500 to 2500 nm), the two pieces of SLG on glass show an ~4.5% absorption (originating from the 2.3% intrinsic absorption of SLG), indicating that this sample can be used as a SA in a wide spectral range.

The experimental setup for the graphene Q-switched TDFL is shown in Fig. 2. The adopted double-clad Tm^{3+} -doped silica fiber (Nufern Co.) was the 10/130 μm type with 0.15/0.46 numerical aperture (NA) and core-doped Tm^{3+} of ~2 wt. % concentration. The cladding absorption of the fiber at ~793 nm was measured with the cut-back method to be ~3 dB/m. The pump source was one 35 W 793 nm LD with 100 μm (0.22 NA) pigtail fibers, which was launched into the Tm^{3+} fiber through a fiber combiner with coupling efficiency of ~95%.

At the rear end, a high-reflection mirror ($R = 99.8\%$ at 2 μm) provided feedback, and this mirror combined with the perpendicularly cleaved output-end fiber facet (~3.5% Fresnel reflection) completed the laser cavity. The graphene glass plate was fixed on a five-dimensional stage and inserted inside the laser cavity so that the laser light passed perpendicularly through the graphene layer. One plano-convex lens ($f = 12$ mm) was used to collimate the laser light before it passed through the graphene, leading to an increase of several times of the laser beam size (which can be tuned by longitudinally displacing the graphene position) when it interacted with the graphene. The 3.2 m long Tm^{3+} fiber was wrapped on a convectively cooled copper drum with a diameter of 10 cm. Due to the quasi-three-level nature of the laser, efficient cooling the fiber is critical for achieving high

Fig. 2. Experimental setup of the Q-switched Tm^{3+} fiber laser. LD, laser diode.

slope efficiencies. At the output end, a dichroic mirror ($R > 99.9\%$ at 793 nm, 0°) was used to filter the unabsorbed pump light. The laser output power was measured with an OPHIR power meter (F150A-SH, Ophir Optonics Ltd.) and the laser spectrum was tested with a triple-grating spectrometer (Zolix Co.) with a spectral resolution of 0.2 nm. The laser pulsing dynamics were recorded with a 500 MHz Agilent oscilloscope (DSO5054A) combined with an InGaAs detector.

When the 2 μm laser operation was initiated with pump power over threshold and the graphene glass plate position was carefully adjusted, stable Q-switching operation of the TDFL occurred, which could be sustained over 5 W output power. Further increasing the pump led to randomizing the pulses. The 2 μm laser output characteristics under Q-switching operation are shown in Fig. 3. The laser power increases linearly with pump power, with a slope efficiency of 26% with respect to the launched 793 nm pump. The laser threshold is ~2.5 W, and the maximum output power is 5.2 W, which is the highest among all graphene-based mode-locked or Q-switched fiber lasers [16–19], to the best of our knowledge. Further increasing the pump power resulted in burning of the graphene. The high average power achieved can be attributed to the large laser beam size crossing the graphene (improve its power damage threshold) and high pump ratios. The comparatively low slope efficiency was attributed to the incurred losses from free-space coupling, glass absorption, and fiber fusion splicing. Further expanding the laser beam size with a specially designed lens (e.g., with longer focus length and larger diameter) can further improve the power damage threshold of the graphene. In this case, damage to the gain-fiber facet will be the main factor that limits the power scaling. This method together with large-mode-area gain fibers can be used to achieve high output power at a new level in fiber lasers.

The laser spectra of the Q-switched TDFL and that under CW operation at the 5 W level are shown in Fig. 4. The spectrum is centered at ~2005 nm with an envelope bandwidth of about 15 nm. Many peaks appear in the spectrum, showing that many longitudinal modes oscillated simultaneously because of high cavity gain and because no mode selecting elements were adopted. Compared with the CW mode, Q-switching operation produced many more oscillating longitudinal modes in the laser cavity due to higher laser peak power.

Fig. 3. Output of the Q-switched Tm^{3+} fiber laser. The laser threshold is around 2.5 W, and the slope efficiency is about 26%. Square dots are measured data and the solid line is for guiding the eye.

Fig. 4. Laser spectra of the Q-switched Tm^{3+} fiber laser (a) with and (b) without graphene Q switching at the 5 W output level.

The laser pulse trains obtained at the 3 and 5 W output levels are shown in Figs. 5(a) and 5(c). At the 3 W level, the intensity stability between different pulses is around 90%, which decreased to $\sim 80\%$ at the 5 W output level. The intensity fluctuation resulted mainly from instability of the free-space coupling. Isolating the environmental disturbance (e.g., air flow) incurred from free-space coupling will greatly improve the stability of the laser. On the other hand, the time jitter (time instability) is comparatively low, showing somewhat high periodic stability.

Single pulse characteristics measured at these two power levels are shown in Figs. 5(b) and 5(d). The pulse width (FWHM) decreased from 470 ns at the 3 W level to 320 ns at the 5 W level. These pulse widths are by far narrower than the previous Q-switched laser pulses (1–4 μs) with graphene [18,19], which can be accounted for by the shorter fiber length adopted and large modulation depth of the double-piece SLG configuration in our work. The single pulse shows a nearly Gaussian shape. The lack of smoothness indicated in the pulse was due to the comparatively low sampling rate in the measurement because these two single pulses were just the zoom-in ones from their corresponding pulse train. The single pulse measured with an adequate sampling rate [inset of Fig. 5(b)] shows mode-locking-like characteristics on the pulse envelope.

To confirm that the Q-switching operation here was induced by graphene, we translated the graphene glass

Fig. 5. Laser pulse train of the Q-switched Tm^{3+} fiber laser at (a) 3 W and (c) 5 W output levels; and single pulses at outputs of (b) 3 W and (d) 5 W. Inset of (b) shows a single pulse at 3 W measured with a high sampling rate.

Fig. 6. (a) Repetition rate and pulse width and (b) pulse energy and peak power of the Q-switched Tm^{3+} fiber laser as a function of launched pump power. The dots indicate the measured data while the solid lines are for guiding the eye.

plate in the transverse direction perpendicular to the cavity axis. When the laser spot was moved out from the graphene region, Q-switching pulses vanished. When the laser spot was moved into the graphene region again, pulsing operation reappeared.

The detailed evolution of the pulse repetition rate and pulse width as functions of pump power are shown in Fig. 6(a). The pulse repetition rate increases nearly linearly from 73 kHz at threshold pump to 280 kHz at the maximum output. On the other hand, the pulse width decreases from 1 μs to 320 ns. These changing trends of pulse repetition rate and pulse width show the typical features of Q-switched lasers. The detailed evolution of the pulse energy and peak power with pump are shown in Fig. 6(b). The peak power increases nearly linearly with pump (the maximum peak power is 56 W), while the pulse energy shows a nonlinear increase with the maximum pulse energy being $\sim 18 \mu\text{J}$. The 320 ns pulse width and 18 μJ pulse energy are by far narrower and higher than those in previous graphene Q-switched reports [18,19].

The output beam propagation characteristic was dictated by the Tm^{3+} fiber core (10 μm , 0.15 NA). The normalized frequency V of this kind of fiber at 2005 nm is about 2.343, less than the single-mode condition of $V \sim 2.405$. This guarantees the fundamental-mode operation and high beam quality of the fiber laser. The average output power stability was monitored with the powermeter during a period of 30 min (1 record per minute), showing a RMS power fluctuation of $<5\%$.

In conclusion, a high average power (over 5 W) Q-switched 2 μm TDFL with graphene has been realized through transforming the intracavity interacting laser beam size passing through the modulation elements. In stable operation, pulse energy of more than 18 μJ and a repetition rate higher than 280 kHz can be achieved. The average power has been enhanced by more than 1 order of magnitude (compared with previously reported results), which can be directly used in many applications or act as an efficient seed for MOPA operation. This kind of passive Q-switching technique based on laser-beam harnessing can be readily extended into all other passively Q-switched lasers with restrained damage-threshold modulation elements (semiconductor SAs, carbon nanotubes, etc.), thus opening up a new method

for realizing high-power pulsed lasers with a simple and low-cost structure.

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