A compact graphene Q-switched erbium-doped fiber laser using optical circulator and tunable fiber Bragg grating*

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We demonstrate a passively Q-switched tunable erbium-doped fiber laser (EDFL) based on graphene as a saturable absorber (SA). A three-port optical circulator (OC) and a strain-induced tunable fiber Bragg grating (TFBG) are used as the two end mirrors in an all-fiber linear cavity. The Q-switched EDFL has a low pump threshold of 23.8 mW. The pulse repetition rate of the fiber laser can be widely changed from 9.3 kHz to 69.7 kHz by increasing the pump power from 23.8 mW to 219.9 mW. The minimum pulse duration is 1.7 μs and the highest pulse energy is 25.4 nJ. The emission wavelength of the laser can be tuned from 1560.43 nm to 1566.27 nm by changing the central wavelength of the strain-induced TFBG.

Keywords: fiber lasers, Q-switching, wavelength tunable operation, graphene saturable absorber

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1. Introduction

There is growing interest in compact Q-switched laser sources because of their potential applications in fiber optical sensing, micromachining, metrology and telecommunications.[1–4] Passively Q-switched fiber lasers based on saturable absorbers (SAs), requiring no additional electronic switching components, have significant advantages over the actively Q-switched ones in compactness, simplicity and flexibility of implementation. To date, different kinds of SAs have been used to achieve passively Q-switched pulses, such as transition metal-doped bulk crystals,[5] semiconductor saturable absorber mirrors (SESAMs),[6] and single-wall carbon nanotubes (SWNTs).[7–9] However, bulk crystal SA requires extra lens to couple light into the fiber, which increases the complexity of optical alignments. SESAM has a narrow tuning range and requires complex fabrication and packaging. With SWNT, it often needs to control the diameter or chirality of a nanotube for obtaining saturable absorption in a desired wavelength range.[10] Nanotubes not in resonance may introduce an undesired large non-saturable loss in a tunable laser. Recently, graphene has emerged as an innovative SA due to its ultrafast saturation recovery time, low saturation threshold and ultra broad wavelength-independent saturable-absorption range,[11–15] therefore, the graphene-based passively Q-switched fiber laser has attracted increasing research interest. Using the fiber ring cavity configuration and exploiting a tunable bandpass filter, Popa *et al.*[16] experimentally demonstrated a wideband-tunable Q-switched erbium-doped fiber laser (EDFL) with a graphene SA. The laser produced pulses with a duration of ~ 2 μs and tunable wavelength range from 1522 nm to 1555 nm. With a similar method, Cao *et al.*[17] obtained stable Q-switched pulses with a tunable wavelength range of over 50.6 nm. However, it is expensive to use commercial tunable bandpass filters for wavelength tuning in the Q-switched fiber lasers. Zhou *et al.*[18] reported on a tunable graphene Q-switched EDFL, in which three subring resonators constructed with three 3-dB couplers were used to suppress the self-mode locking (SML) effect. The use of subring resonators gives a complicated cavity configuration. Using a short linear-cavity structure, Wei *et al.*[19] presented a graphene Q-switched EDFL with two fiber Bragg gratings (FBGs).

In this paper, we demonstrate a simple and cost-effective tunable EDFL passively Q-switched by a graphene SA. A linear cavity is constructed by using a three-port optical circulator (OC) as the high-reflection mirror and a strain-induced tunable fiber Bragg grating (TFBG) as the partial-reflection mirror and wavelength selector. With this scheme, no SML effect on the Q-switched oscillation is observed. The Q-switched EDFL has a low Q-switching threshold of 23.8 mW. The pulse repetition rate of the laser can be widely adjusted from 9.3 kHz to 69.7 kHz by increasing the pump power from 23.8 mW to 219.9 mW. The output wavelength of the laser can be tuned from 1560.43 nm to 1566.27 nm by adjusting the central wavelength of the strain-induced TFBG.

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2. Experimental setup

Our proposed graphene-based passively Q-switched EDFL is schematically shown in Fig. 1. A linear cavity configuration is adopted, where a three-port OC and an FBG are used as the two end mirrors. The port-to-port insertion loss of the OC is about 0.7 dB. The FBG has a central wavelength of 1560.4 nm, a 3-dB spectral bandwidth of 0.1 nm and a reflectivity of 95%. A 0.6-m heavily doped erbium fiber (EDF, Liekki Er80-8/125) with a peak absorption of 80 dB/m at 1530 nm is used as a gain medium. Other fiber used in the cavity is the standard single mode fiber (SMF). The laser is pumped by a commercial 980-nm laser diode (LD) through a wavelength division multiplexer (WDM). The overall length of the laser cavity is about 2.8 m. The assembled graphene SA as a passive Q-switcher is placed between the WDM and the FBG. In this study, monolayer graphene film is grown on Cu foil by the chemical vapor deposition (CVD) method, similar to that reported in Ref. [20]. The surface of the graphene on Cu is spin-coated with poly (methyl methacrylate) (PMMA) and the PMMA/graphene/Cu foil is baked on a hot plate at 100 °C for 3 min and then 120 °C for 5 min. Then the Cu foil is etched in an aqueous solution of 10-wt% $Fe(NO_3)_3$. After the Cu foil is completely etched, the PMMA/graphene is washed in DI water several times to remove Fe^{3+} and NO_3^-. The PMMA/graphene is transferred onto the end-face of a fiber connector and the PMMA layer is removed by the acetone vapor. The transfer process is repeated four times to obtain 4-monolayer graphene onto the end-face of a fiber connector to form a graphene-based SA. The linear insertion loss of our graphene SA is about 1.5 dB. The laser output from the FBG with a 5%-transmission is measured by an EXFO optical power meter, an optical spectrum analyzer (Yokogawa AQ 6370C) and an oscilloscope (Tektronix TDS3052C) together with a 2-GHz bandwidth photodetector.

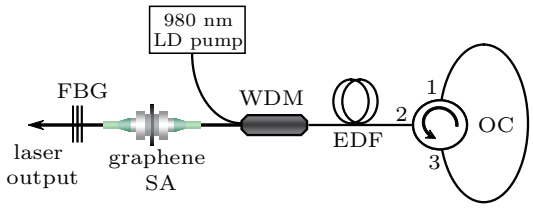


Fig. 1. (color online) Experimental setup of the proposed graphene-based passively Q-switched laser, composed of fiber Bragg grating (FBG), graphene saturable absorber (SA), 980-nm laser diode (LD) pump, wavelength division multiplexer (WDM), erbium-doped fiber (EDF), and optical circulator (OC).

3. Experimental results and discussion

Continuous wave operation starts at a pump power of 19.2 mW and stable Q-switched pulses are achieved when the pump power is increased to 23.8 mW. We confirm experimentally that the pulse operation of the laser is caused by the graphene-based Q-switcher. Without a graphene SA in the cavity, no Q-switching is obtained. Figure 2 shows typical oscilloscope traces of the Q-switched pulse trains in time domain under two different pump powers. The pulse repetition rate of the fiber laser can be widely changed by increasing the pump power, as shown in Fig. 3. At 23.8-mW pump power, the pulse repetition rate is 9.3 kHz while increasing the pump power to 219.9 mW, the repetition rate is increased about 7.5 times to 69.7 kHz. At every specific pump power and repetition rate, the Q-switched pulse output is stable and no significant pulse jitter is observed on the oscilloscope. By reducing the insertion loss of the graphene SA and using a higher concentration EDF to increase the pumping rate, the pulse repetition rate can be further raised because the recovering time of graphene SA is far less than the pulse separation.[21] In the experiment, no amplitude modulations in these pulse trains are observed, which indicates that there is no SML effect in the Q-switching operation. With our proposed laser cavity configuration, the SML effect can be effectively suppressed by the narrow-band filtering of the FBG. In addition, the intracavity OC works not

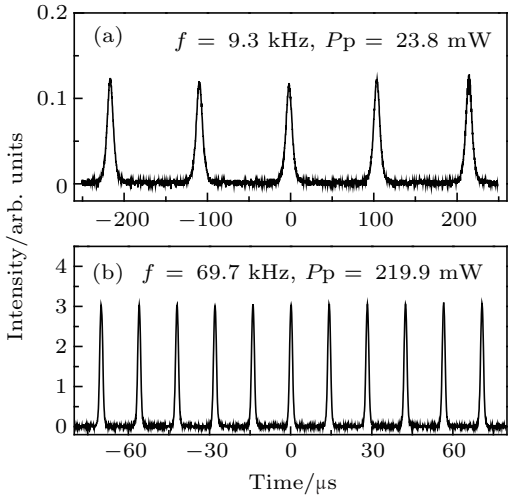


Fig. 2. Typical oscilloscope traces of the Q-switched pulse trains under different pump powers: (a) 23.8 mW and (b) 219.9 mW.

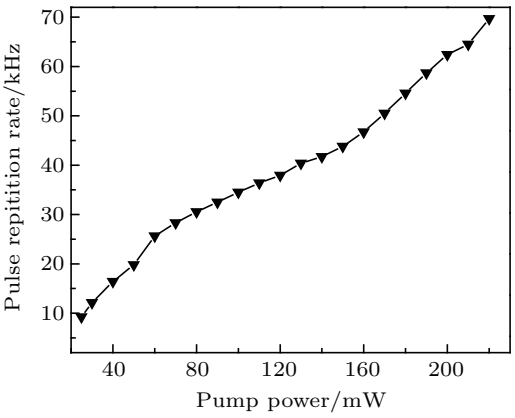


Fig. 3. Pulse repetition rate versus pump power.

only as a high reflection mirror for the linear laser cavity, but also as a router for recycling the residual pump light and increasing the laser pumping efficiency.

Figure 4 shows the pulse duration and pulse energy each as a function of pump power. By increasing the pump power, the pulse duration is shortened and the pulse energy is increased monotonically. At a maximum pump power of 219.9 mW, a minimum pulse duration of 1.7 μs, shorter than that obtained in Ref. [16], is achieved as shown in Fig. 5(a), and the corresponding pulse energy reaches 25.4 nJ. Figure 5(b) shows the optical spectrum of the Q-switched pulses. The central wavelength is located at 1560.43 nm and the 3-dB bandwidth is about 0.10 nm. With the further increase of the pump power, the Q-switched pulse train becomes unstable or even disappears, which may be due to the thermal damage to the graphene SA under a high pump power. In our experiment, to protect the graphene-based Q-switcher from thermo-damaging, the Q-switched EDFL may be operated with the pump power below 220 mW. The pulse duration can be further reduced by shortening the cavity length since the pulse duration is dependent on the cavity length in a passively Q-switched fiber laser.[6] Moreover, the pulse energy can be scaled up by further increasing the pump power and improving the thermal damage threshold of graphene SA, for example, by depositing the graphene on a D-shape fiber or a tapered fiber.[22,23]

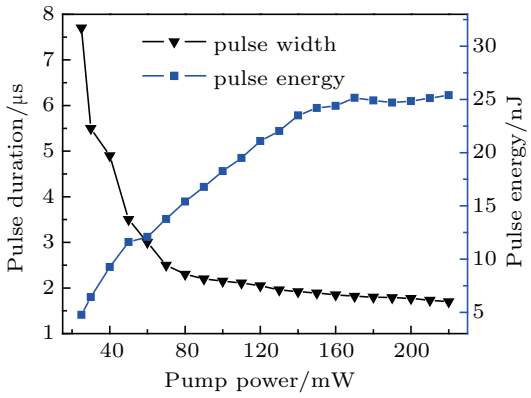


Fig. 4. (color online) Pulse duration and pulse energy versus pump power.

The output wavelength of the Q-switched EDFL can be continuously tuned by adjusting the central wavelength of the FBG. A tunable wavelength range from 1560.43 nm to 1566.27 nm is achieved by applying an axial strain to the FBG under a pump power of 120.1 mW, as shown in Fig. 6. In this tunable wavelength range, the average output power and pulse repetition rate are measured to be ∼ 0.81 mW and ∼ 37.9 kHz, with maximum deviations of 0.07 mW and 0.6 kHz, respectively. The peak power fluctuations of the spectra are smaller than 2.2 dB. The 3-dB bandwidth is 0.1 ± 0.04 nm over the tuning range. In our experiment, the tunable wavelength range of 5.84 nm is limited by the low mechanical strength of the FBG, which is fabricated with the conventional processes of pulsed ultraviolet exposure and mechanical stripping. The FBG can be damaged with the further increase of the axial strain on it. The tunable wavelength range can be further extended by using strain-induced tunable cascaded FBGs or a highly stretchable FBG.

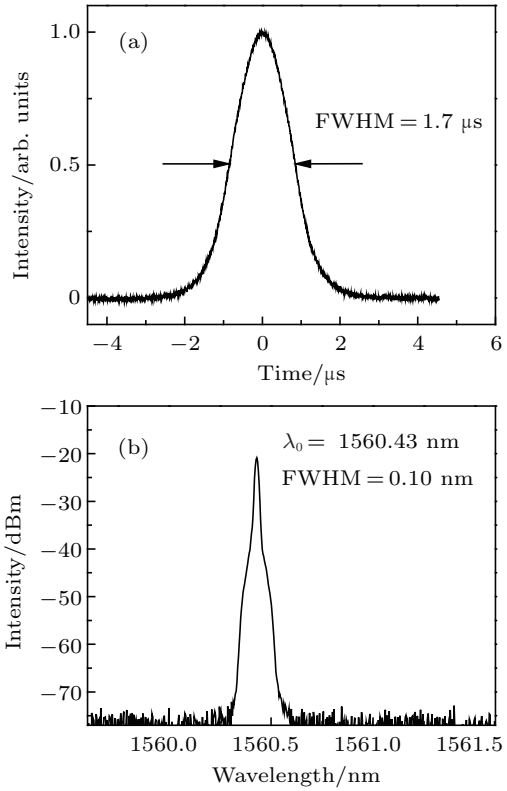


Fig. 5. Single-pulse envelope (a) and optical spectrum (b) under a pump power of 219.9 mW.

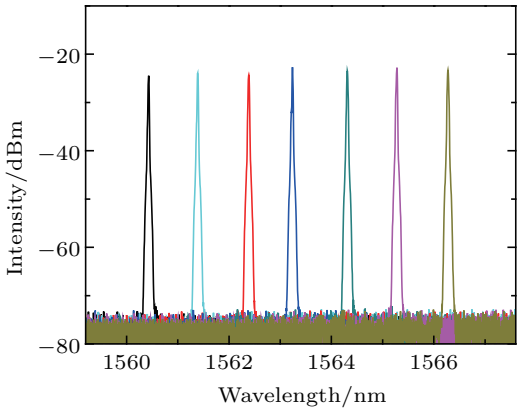


Fig. 6. (color online) Laser output spectra at different wavelengths under a pump power of 120.1 mW.

4. Conclusion

In this paper, we experimentally demonstrate a compact graphene-based tunable Q-switched EDFL with a linear-cavity configuration. The linear cavity is constructed by using a

three-port OC and a strain-induced TFBG as the two end mirrors. The laser has a low pump threshold of 23.8 mW, a minimum pulse duration of 1.7 μs and a maximal pulse energy of 25.4 nJ. The pulse repetition rate of the fiber laser can be widely changed from 9.3 kHz to 69.7 kHz by increasing the pump power from 23.8 mW to 219.9 mW. By exploiting a strain-induced TFBG, the laser operation wavelength is tunable in the range from 1560.43 nm to 1566.27 nm. The simple and cost-low tunable Q-switched EDFL is a promising light source for fiber optical sensing, metrology, laser micromachining, and telecommunications.

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