Q-switched pulse generation from an all-fiber distributed Bragg reflector laser using graphene as saturable absorber

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A Q-switched distributed Bragg reflector fiber laser using a graphene passive saturable absorber is proposed in a cavity consisting of a fiber Bragg grating and Faraday rotator mirror as end mirrors, together with a highly doped erbium-doped fiber as a gain source. The laser has a Q-switched threshold of about 28 mW and a tunable repetition rate of 10.4–18.0 kHz with varying pump power. The shortest pulse width obtained from the system is 3.7 μs, with a maximum pulse energy and peak power of 22.2 nJ and 3.4 mW, respectively.

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Distributed Bragg reflector (DBR) fibers have high potential as compact sources for various applications due to their short cavity and simple configuration[1−5], which enable them to yield a narrow linewidth laser output[6,7]. DBR lasers have the advantage of robust single-frequency operation; they can also act as a multimode source with a much larger emission bandwidth[8,9]. Significant interest has been generated by the applications of Q-switched lasers in generating high-power optical pulses, including those demonstrated using crystals[10], and more recently, in graphene-based Q-switched fiber lasers[11] which have potential uses in sensors, medicine, and photoconductive switching, among others[12,13]. Limited reports are available on the generation of Q-switched pulses in DBR fiber lasers, and these studies involve complicated fabrication processes, such as in the case of the Q-switched tapered DBR laser[14]. In this regard, the application of graphene as a saturable absorber (SA) will be a very interesting option in the development of a simpler and more compact Q-switched DBR fiber laser. Graphene is a densely packed monolayer carbon atom in a honeycomb crystal lattice that can be used as a SA through Pauli blocking[15]. Graphene has significant applications in passive Q-switched lasers[16−19], and exhibits superior performance compared with semiconductor-saturable-absorber-mirrors and single-wall carbon nanotubes[20−24] due to its zero bandgap and wide wavelength range. In this letter, a Q-switch DBR fiber laser is developed using a highly doped erbium-doped fiber (EDF) as the gain medium combined with fiber Bragg grating (FBG) and Faraday rotator mirror (FRM) acting as end mirrors. Fiber laser Q-switching is accomplished by placing a graphene layer inside a cavity, which acts as the SA. The system is capable of generating stable optical pulses with a maximum peak power of 3.4 mW, pulse energy of 22.2 nJ, and full-width at half-maximum (FWHM) spectral width of $\leq$0.05 nm at a maximum pump power of approximately 74 mW. To the best of our knowledge, this letter presents the first demonstration of a passive Q-switched DBR fiber laser with graphene as a SA.

Figure 1 shows the experimental setup for the proposed graphene-based Q-switched DBR laser.

The EDF absorption coefficients are between 11 and 13 dBm^{-1} at 980 nm and about 18 dBm^{-1} at 1 550 nm, with an erbium ion concentration of 960 ppm. A 980-nm laser diode (LD) is used as the fiber laser pump source and is connected to the 980-nm port of a wavelength division multiplexer (WDM). The common output of the WDM is connected to the input port of the FBG, with central wavelength of 1 557 nm and reflectivity of about 70%, which is part of the DBR laser cavity and acts as the 'front mirror'. The FBG output is connected to the SA, which is formed by sandwiching the graphene layers between two connectors. In turn, the output of the SA is connected to a 2.7-m-long EDF (Metrogain Type-12, Fibercore, UK), which acts as the gain medium for the proposed laser. The other end of the EDF is connected to a FRM, which serves as the 'back mirror' for the linear cavity. The laser will then oscillate in the cavity formed by FBG and FRM, and the filtered output is extracted through the WDM via the 1 550-nm port. The output from the 1 550-nm port is equally split into two parts by a 3-dB coupler. One of the parts is analyzed by an optical spectrum analyzer (OSA) (AQ6317, YOKOGAWA, Japan) for the generated spectrum, whereas the other part is used in the analysis of the laser output pulse characteristics using a photodetector connected to a LeCroy 352A oscilloscope.

The SA is created by initially depositing a few graphene layers onto one of the fiber ferrules using the optical deposition technique. The graphene itself is obtained in the form of graphene flakes suspended in an N-methyl pyrrolidone (NMP) solution. The fiber ferrule is dipped into this solution. The other end of the patch cord is connected to an amplified spontaneous emission (ASE) source with an output power of about 10 dBm. As a result of the thermophoresis effect[17,21], layers of graphene are slowly formed on the surface of the fiber ferrule. Subsequently, the fiber ferrule is removed from the solution and allowed to dry to get rid of any excess NMP solution before being connected to an FC/FC fiber adaptor. The other end of the adaptor is connected to another fiber

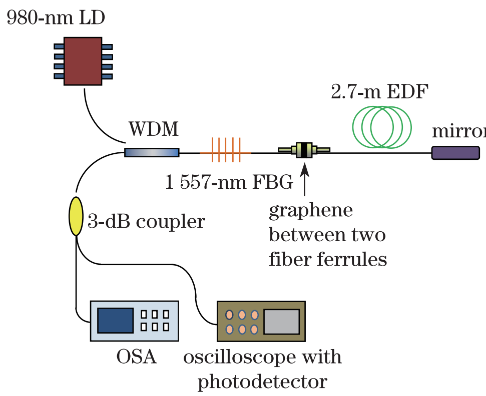

Fig. 1. Experimental setup for the proposed graphene-based Q-switched DBR laser.

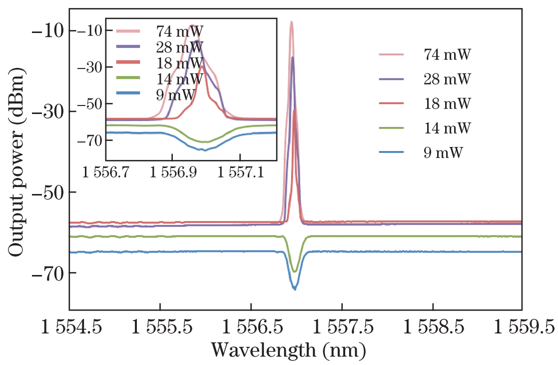

Fig. 2. (Color online) Laser output spectrum with respect to different pump powers.

ferrule, which is in contact with the graphene layers. This setup creates the intended SA, which functions as a Q-switching device to generate the pulse output with an insertion loss of about 2 dB.

Figure 2 shows the output spectra of the graphene-based Q-switched DBR fiber laser taken from the OSA, with a spectral resolution of 0.02 nm at five different pump powers, including 9, 14, 18, 28, and 74 mW, respectively. As shown in Fig. 2, lasing is not initiated until the pump power of 14 mW is reached. At 18-mW pump power, continuous wave (CW) laser operation in the fiber laser is first observed. This observation is deduced from the plot of the average output power against pump power, as shown in Fig. 3. Above the threshold value, the spectrum linewidth narrows down, thus producing a FWHM of less than 0.05 nm at a 1557-nm center wavelength. The inset in Fig. 2 provides an expanded scan for the same trace. The change in pump power significantly varies the output power amplitude, with the highest output power measured to be roughly –8 dBm (0.16 mW) at 74-mW pump power, which is considered as the peak OSA value in the logarithmic scale. These measurements are taken with the graphene SA already in place. An interplay emerges between the gain (in the gain medium) and the loss (in the cavity) due to the SA. During the initial stage, as the population inversion builds up, a low-power ASE output will be produced, which is blocked by the SA. This process allows a rapid population inversion build-up in higher states; a sudden release of energy from this state to a lower state will occur, which will then saturate the SA and allow a Q-switched pulse to be generated in the oscillating cavity[25]. In the generation of Q-switched pulses, two important contributors are the gain medium and the cavity design[26]. Therefore, cavity design optimization is crucial.

Figure 3 shows the average output power against a 980-nm pump power. The average output power is measured using an integrating sphere that collectively gathers all the proposed laser outputs. From Fig. 3, the lasing threshold power can be deduced to be approximately 18 mW, with an almost linear characteristic. The laser output slope efficiency above the threshold value is about 0.7%. Even at the maximum pump power of 74 mW, the measured output power is already about 0.4 mW, whereas the laser has yet to reach saturation. These results indicate that higher output powers are achievable within this system. However, this concept cannot be demonstrated in the current setup due to the graphene layer damage threshold. Nonetheless, this issue could be solved if the graphene sample is further optimized.

Figure 4 shows the variations in the repetition rate and pulse width of the system against different 980-nm pump powers.

As shown in Fig. 4, the repetition rate increases with increasing pump power, starting from 10.4 kHz at a pump power of 28 mW (Q-switching threshold) to a maximum value of 18.0 kHz at a pump power of 74 mW. This result indicates that the pulse repetition rate of this graphene-based Q-switched DBR can be tuned to over 8.0 kHz by changing the pump power. Furthermore, the Q-switching threshold (28 mW) in this system is much lower than those achieved by using graphene as SA in a ring EDF laser (EDFL), as reported in Refs. [16,17], with Q-switching threshold values of 74 and 33 mW,

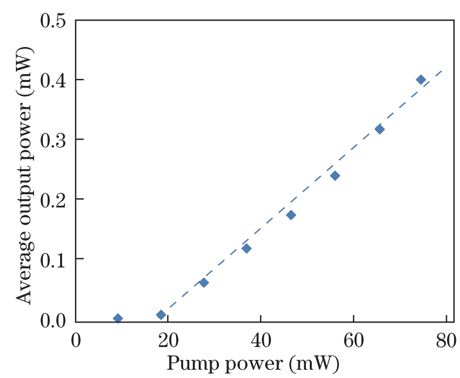

Fig. 3. Average output power against pump power.

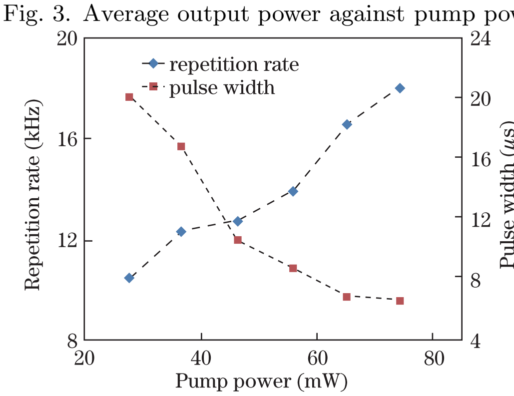

Fig. 4. Repetition rate and pulse width variation against pump power.

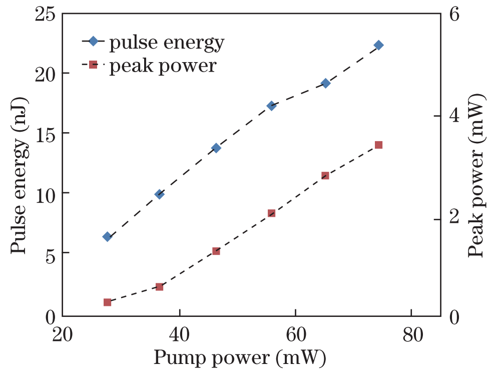

Fig. 5. Pulse energy and peak power versus pump power.

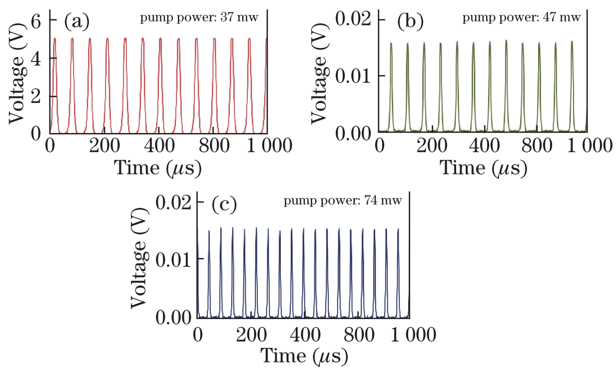

Fig. 6. Q-switched output pulse trains taken at different pump powers: (a) pump power of 37 mW with repetition rate of 12.3 kHz and pulse width of 16.8 μs; (b) pump power of 47 mW with repetition rate of 12.8 kHz and pulse width of 10.6 μs; (c) pump power of 74 mW with repetition rate of 18.0 kHz and pulse width of 6.6 μs.

respectively. The advantage of a Q-switched fiber laser is that it can be tuned by adjusting the pump power, which is not the case for mode-locked laser systems that require fine cavity adjustments. Theoretically, in a Q-switched laser, an increase in pump power would also increase the laser gain, which results in the saturation of the SA. The saturation level governs pulse generation, so increasing the pump power would eventually lead to an increase in the pulse repetition rate[27]. In the case of pulse width, the measured value at the Q-switched threshold is about 20.2 μs, with the pulse width rapidly decreasing by half (10.6 μs) at twice the pump power (46 mW). However, further increase in pump power does not result in significant changes in the pulse width, with an observed pulse width reduction of only 3.7 μs as the pump power is increased to around 65 mW. The shortest pulse width of 6.6 μs is obtained at a maximum pump power of 74 mW.

Figure 5 shows the variations in energy and peak power of the generated pulses with respect to the 980-nm pump power. From Fig. 5, both the pulse energies and peak powers respond almost linearly with increasing pump power, with the lowest pulse energy of 6.5 nJ obtained at the Q-switching threshold of 28 mW.

Increasing the 980-nm pump power results in an increase in pulse energy until the highest pulse energy value of 22.2 nJ is obtained at the maximum pump power of the system. The pulse energies obtained in this setup is comparatively larger than those reported in Ref. [18], wherein graphene is used as a SA in a ring EDFL, with the highest pulse energy of 16.7 nJ obtained at a pump power greater than 80 mW. Similarly, the peak power of each generated pulse is lowest at the Q-switching threshold, with an average of 0.3 mW. Increasing the pump power results in a corresponding increase in the peak power of the pulses, with the maximum peak power of 3.4 mW obtained at a 74-mW pump power.

Figure 6 shows the output pulse trains obtained from the proposed Q-switched DFB laser at different pump powers. At a pump power of 37 mW, a pulse train with a repetition rate of 12.3 kHz and pulse width of 16.8 μs is obtained. Increasing the pump power results in a pulse train with a slightly higher repetition rate (12.8 kHz) and shorter pulse width (10.6 μs), which is expected in this system. Further increase in pump power yields similar results, with the maximum pump power generating the highest repetition rate of 18.0 kHz and the shortest pulse width of 6.6 μs.

All the generated pulse trains are clean and exhibit a smooth and uniform pulse. This observation confirms that the proposed fiber laser is free from any self-locking mode. To the best of our knowledge, this research is the first successful demonstration of an all-fiber DBR laser with a graphene-based passive SA.

In conclusion, a Q-switched DBR-based fiber laser with end mirrors formed from FBG and FRM is proposed and demonstrated. The DBR incorporates graphene laser as a passive SA, and a high-gain EDF acting as the primary gain medium to generate a stable Q-switched output. The laser output has a CW threshold of 18 mW and a Q-switch threshold of 28 mW, with a slope efficiency of 0.7%. The output spectrum has less than 0.05-nm FWHM taken at 1557 nm. The peak OSA measured output power is −8 dBm. As the pump power is varied from 28 to 74 mW, the repetition rate of the generated pulses also changes from 10.4 to 18.0 kHz. The pulse width also varies with pump power from 20.2 to 3.7 μs over a similar range. At the maximum pump power, the highest output pulse energy is about 22.2 nJ, whereas the maximum peak power is 3.4 mW. The generated pulse trains are clean with a smooth and uniform pulse. Thus, they can have potential applications in the fields of communications and sensor sources.

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