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A Q-switched erbium-doped fiber laser with a graphene saturable absorber

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Abstract

We demonstrate a simple, compact and low cost *Q*-switched erbium-doped fiber laser (EDFL) exploiting a graphene saturable absorber (GSA) for possible applications in metrology, sensing and medical diagnostics. The EDFL operates at 1560 nm with repetition rates of 31.3 kHz and 25 kHz with GSA1 and GSA2, respectively, at pump power of 120 mW. The repetition rate is smaller with a lower pump power. It has a pulse width of 7.5 μs and pulse energy of 43.7 nJ with GSA2 at 120 mW pump power. It is also observed that a thicker layer of graphene produces a *Q*-switched fiber laser with a lower pump threshold and a higher output energy, but smaller repetition rate and pulse width.

1. Introduction

Q-switched fiber lasers are of great interest because of their versatile applications to remote sensing, range finding, medicine, material processing and telecommunications [1, 2]. They can be obtained through active [3] or passive techniques [4]. Compared to the active technique, passively *Q*-switched fiber lasers possess the attractive advantages of compactness, simplicity and flexibility in design. They have been intensively investigated using different kinds of saturable absorbers (SAs) [5–7] such as transition-metal-doped crystals [8], semiconductor saturable absorber mirrors (SESAMs) [9] and single-wall carbon nanotubes (SWCNTs) [10]. Saturable absorbers are materials whose absorptions decrease with increasing irradiances. In saturable absorbers, the molecules absorb radiation so strongly that substantial numbers of atoms can be excited to upper levels and significant changes occur in the absorption rates of the materials. When the ground and excited state populations are almost equal, the absorption becomes very small and the material is said to be 'bleached', or 'saturated'. An increase in irradiance leads to further bleaching until the material switches from absorbing to transmitting, thereby allowing the formation of a very intense and short (a few nanoseconds) pulse [11–13].

Recently, graphene has gained tremendous attention for SA applications. This is due to the gapless linear dispersion of Dirac electrons in graphene, which allows a broadband operation. The graphene is a flat monolayer of carbon atoms tightly packed into a two-dimensional (2D) honeycomb lattice. It can be stacked to form 3D graphite, rolled to form 1D nanotubes and wrapped to form 0D fullerenes [14]. Nair *et al* [15] have demonstrated that, despite being only one atom thick, graphene absorbs a significant ($\pi\alpha = 2.3\%$) fraction of incident white light due to its unique electronic structure. The optical absorption is also found to be frequency independent and proportional to the number of layers [16]. Boe *et al* [17] have recently reported that graphene can provide outstanding saturable absorption, where it has a much lower saturation intensity, larger saturable-absorption modulation depth and a higher damage threshold compared to SWCNTs. Therefore, many techniques have been developed to integrate graphene into fiber devices to construct SAs for passive pulse construction [17], which are mostly based on graphene mode-locked fiber lasers. In this letter, we demonstrate a simple and compact *Q*-switched EDFL using a graphene solution deposited on the end surface of a fiber ferrule, which is then incorporated in a ring laser cavity to act as a saturable absorber. The *Q*-switching performance of the laser is investigated for two different graphene saturable absorbers (GSAs).

2. Experiment

Figure 1 shows an experimental setup for the deposition of graphene onto the end surface of the ferrule, whereby the optical deposition method proposed by Kashiwagi *et al* [18] and Martinez *et al* [19] was used. In the optical deposition method, injecting amplified light to the fiber end will create optical trapping, thermally driven convection flow and thermo-diffusion [20]. The interaction of the laser beam and graphene composite is developed by optical trapping and this will increase the solution temperature due to amplified injected light. The difference in temperature between the fiber ferrule and heated solution creates a thermo-diffusion effect where the graphene flakes are attracted to the cooler fiber ferrule. The graphene flakes (in solution) used in the experiment are supplied by Graphene Research Ltd, and prior to deposition the solution is agitated for 30 min using an ultrasonic bath. Optical radiation from a 1550 nm laser source is amplified by an optical amplifier to 30 dBm and then propagated through a fiber pigtail via an optical circulator. The end surface of the pigtail is dipped into the graphene aqueous suspension and the whole deposition process of the graphene on the fiber ferrule core is monitored by an optical power meter and recorded using a GPIB card connected to a computer through a LabVIEW 7.1 interface. The deposition process is halted when there is a sudden change in power, and from the experiment a rapid increment of the reflected light power is observed after 10 s. The light source is turned off 5 s after the sudden change of power, which indicates that graphene has been deposited on the ferrule end surface. The fiber is then removed from the solution. After water evaporation, the ferrule is connected to another ferrule to form a fiber compatible graphene saturable absorber (GSA).

Figure 2 shows the experimental setup of the proposed compact *Q*-switched EDFL using the fabricated GSA as a passive *Q*-switcher. A 49 cm long bismuth based erbium-doped fiber (Bi–EDF) with erbium ion concentration of 3250 ppm and cutoff wavelength of 1450 nm is used as the gain medium. The Bi–EDF is forward pumped by a 1480 nm laser diode through a 1480/1550 nm wavelength division multiplexer (WDM). Another WDM is placed after the Bi–EDF to remove the excess pump power. The laser output is obtained via a 10 dB optical coupler located after the GSA, which channels out about 10% of the oscillating light from the ring cavity. The output is analyzed using an optical spectrum analyzer (OSA) of 0.02 nm resolution and a 500 MHz oscilloscope with a 6 GHz bandwidth lightwave detector. An optical isolator is incorporated after the optical coupler to ensure that light propagates in a unidirectional manner. The rest of the cavity is made of SMF-28 single-mode fiber. All components used in our setup are polarization independent, i.e. they support any light polarization. No polarization controller (PC) is included in our cavity as we had observed earlier that a PC did not improve our pulse stability. There is no significant pulse jitter observed through the oscilloscope during the experiment. The experiment is carried out for two different GSAs: GSA1 and GSA2. The insertion loss of GSA1 and GSA2 are determined to be around 0.5 dB while the total length of the cavity is measured to be about 25 m. For GSA2, graphene is deposited on both end surface faces of the ferrules and thus it has a thicker graphene layer compared to that on the GSA1.

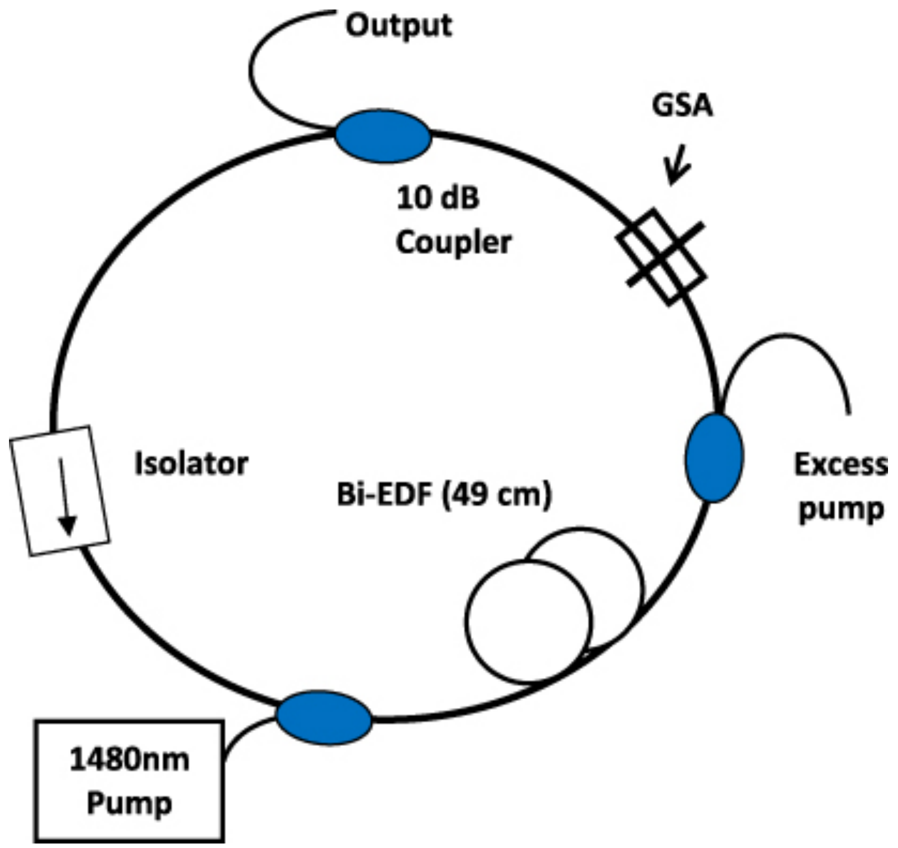

Figure 1. Experimental setup of the proposed graphene based *Q*-switched EDFL.

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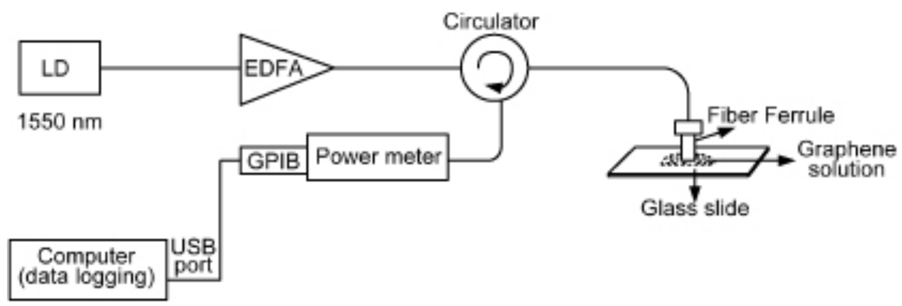

Figure 2. Experimental setup for depositing graphene on the fiber end surface by optical radiation.

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3. Result and discussion

The proposed EDFL started to lase with the passive *Q*-switching mode at the pump power of around 50 mW. The pump threshold was relatively low compared to that of an SWNT or SESAM based *Q*-switched EDFL, mainly owing to a lower saturation intensity of the graphene. Figure 3 compares the oscilloscope traces of the *Q*-switched pulse trains for two different GSAs when the pump power is fixed at the maximum value of 120 mW. As shown in the figure, repetition rates of 31.3 and 25 kHz are obtained with GSA1 and GSA2, respectively. Since a thicker graphene layer means more absorption, it takes a longer time for the GSA2 to bleach and thus its repetition rate is lower than that of GSA1. Unlike a mode-locked fiber laser, where the repetition rate is dependent on cavity length, the repetition rate in a *Q*-switched fiber laser varies with pump power. Figure 4 shows the repetition rate as a function of pump power for both cases. As the pump power increases, more gain is provided to saturate the GSA. Since pulse generation relies on saturation, the repetition rate increases with the pump power as shown in figure 4. For instance, with GSA1, the pulse repetition rate of the *Q*-switched EDFL can be widely tuned from 16.7 to 31.6 kHz by varying the pump power from 55 to 120 mW. At every specific repetition rate and pump power, the *Q*-switching pulse output was stable and no significant pulse jitter was observed on the oscilloscope. The inset of figure 4 shows the output spectrum for the proposed *Q*-switched EDFL configured with FSA1 and GSA2. As shown in the figure, the laser operates at around 1560 nm with a full width at half maximum of around 0.3 nm.

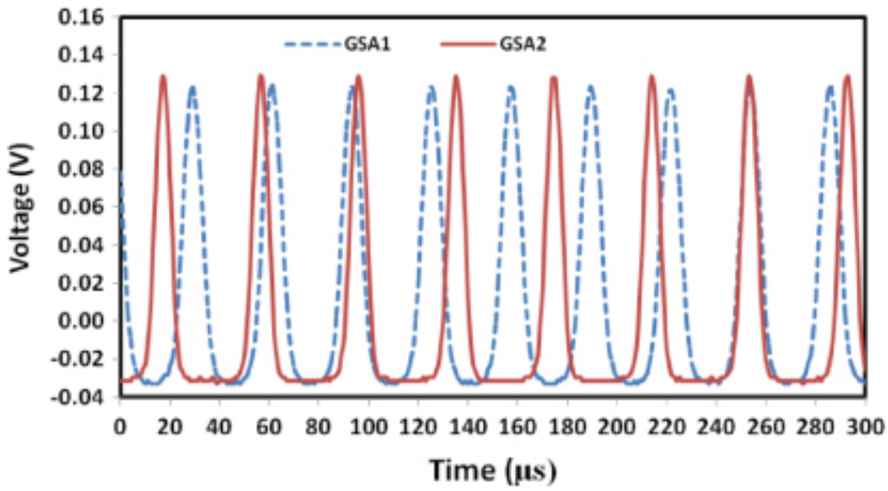

Figure 3. Typical pulse trains for the proposed EDFL configured with GSA1 and GSA2 at a pump power of 120 mW.

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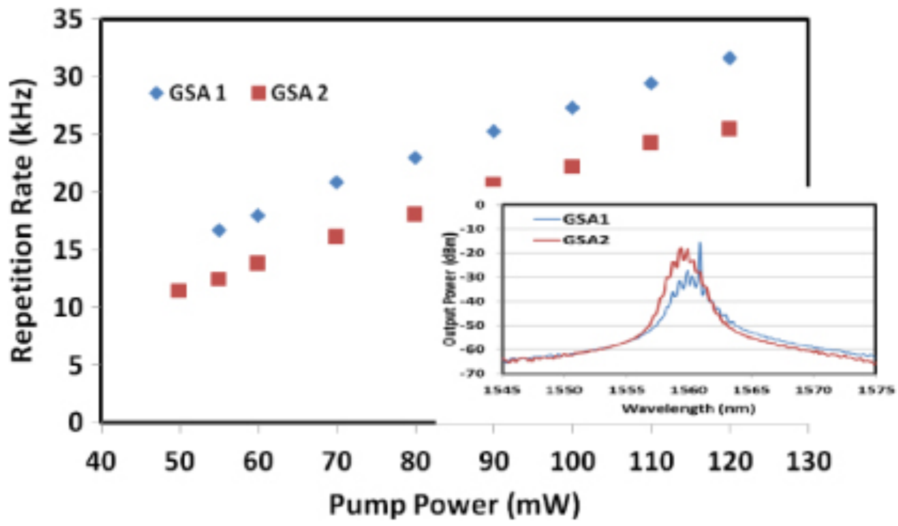

Figure 4. Repetition rate as a function of 1480 nm pump power. The inset shows the optical spectrum of the laser at a pump power of 120 mW.

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Figure 5 shows the pulse width and the pulse energy as a function of the pump power. As seen in the figure, increasing the pump power makes the pulse width narrower and the pulse energy higher for both GSAs. At the pump power of 120 mW, the *Q*-switched EDFL has a pulse width of 7.5 µs and pulse energy of 43.7 nJ using GSA2. A thicker layer of graphene (in GSA2) implies that more atoms are stored in the excited state level, and consequently more stimulated emission occurs when the GSA bleaches. This in turn generates more output power. This explains why the output energy of GSA2 is significantly higher than that of GSA1. The reason is also linked to the observation that using GSA2 yields a lower pulsing threshold. The threshold pump powers for *Q*-switching operation with GSA1 and GSA2 are observed to be 51.3 and 47.6 mW, respectively. These results indicate that graphene has a larger potential for better *Q*-switching and saturable absorption compared to conventional light absorbing components when carefully employed in an appropriate laser system. The proposed EDFL is simple, low in cost and suitable for metrology, environmental sensing and biomedical diagnostics.

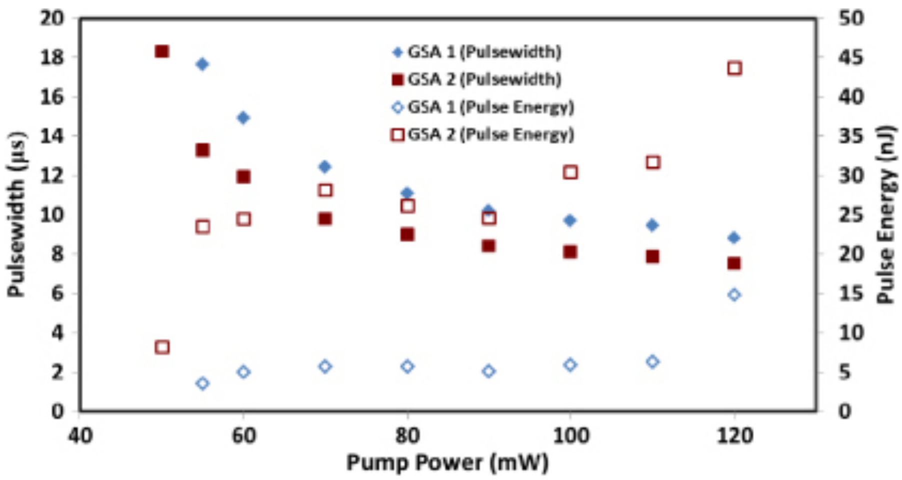

Figure 5. Pulse width and pulse energy as a function of input pump power.

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4. Conclusion

A simple and compact *Q*-switched EDFL is demonstrated using a GSA, which is obtained by depositing the graphene solution on the end surface of a fiber ferrule. It is found that a thicker layer of graphene produces a *Q*-switched fiber laser with a lower pump threshold and higher energy but smaller repetition rate and pulse width. The EDFL operates at 1560 nm with a repetition rate that varies with the pump power. For instance, the repetition rate of the EDFL configured with GSA1 can be widely tuned from 16.7 to 31.6 kHz by varying the pump power from 55 to 120 mW. The EDFL has a pulse width of 7.5 μs and pulse energy of 43.7 nJ with GSA2 at 120 mW pump power.

Acknowledgments

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