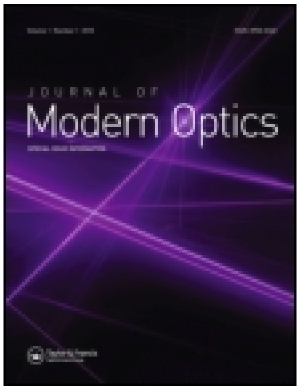

Journal of Modern Optics
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/tmop20

Tunable graphene-based Q-switched erbium-doped fiber laser using fiber Bragg grating

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Version of record first published: 22 Feb 2013.

Journal of Modern Optics, 2013
Vol. 60, No. 3, 202–212, http://dx.doi.org/10.1080/09500340.2013.766767

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Tunable graphene-based Q-switched erbium-doped fiber laser using fiber Bragg grating

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(*Received 17 August 2012; final version received 9 January 2013*)

A graphene-based Q-switched erbium-doped fiber laser (EDFL) with a tunable fiber Bragg grating (TFBG) acting as a wavelength tuning mechanism is proposed and demonstrated. The proposed setup utilizes a newly-developed 'ferrule-to-ferrule transfer' technique to obtain a single graphene layer that allows for Q-switch operation in the EDFL using a highly doped-gain medium. A TFBG is used as a wavelength tuning mechanism with a tuning range of 10 nm, covering the wavelength range from 1547.66 nm to 1557.66 nm. The system has a wide repetition rate range of over 206.613 kHz from 1.387 kHz to 208.000 kHz with pulse durations of between 94.80 μs to 0.412 μs. The laser output is dependent on the pump power, with energy per pulse of 4.56 nJ to 16.26 nJ. The system is stable, with power and wavelength variations of less than 0.47 dBm and 0.067 nm. The output pulse train is free from self-mode locking and pulse jitters.

Keywords: graphene; fiber laser; S-band

1. Introduction

Q-switching is a fundamental technique in generating high energy pulsed lasers, which are important for applications in the fields of laser processing, medicine, environmental sensing, range finding, telecommunications, reflectometry, remote sensing, and material processing [1–7]. Unlike mode-locking, Q-switching has a relatively much longer pulse duration and much lower repetition rate (usually in the kHz range), which corresponds to the time taken between two successive pulses to restore the emitted energy, depending on the lifetime of the electron in the excited state inside the gain medium. For instance, the lifetime of erbium-doped fibers, which is approximately several milliseconds, is not short enough to ultimately yield a high repetition rate in Q-switching, as can be definitely reached by the mode-locking operation after satisfying the specific conditions. Nevertheless, in some aspects, Q-switching has certain advantages over mode-locking in terms of being easier to accomplish compared to mode-locking because there is no requirement for controlling and attaining the equilibrium between the dispersion and nonlinearity of the intra-cavity medium in Q-switching as needed by mode-locking for the purpose of achieving stable operation. Furthermore, Q-switching is able to produce higher pulse energies, higher operation efficiency, and is more cost effective than mode-locking [8]. Q-switching laser operation can be realized either actively or passively. Active Q-switching involves the modulation of the Q-factor by external equipment or components applied in the laser cavity such as electro-optic modulators [9], acousto-optic modulators [10,11], and mechanical rotating choppers. On the other hand, passive Q-switching incorporates a saturable absorber inserted within the laser cavity. In this case, the amount of the photon absorption is determined based on the light intensity passing through the saturable absorber. Generally, passive Q-switching is more difficult to trigger compared with active Q-switching. In spite of this, the passive Q-switching approach is more desirable and more rapidly investigated than active Q-switching due to its advantages of simpler configuration, higher reliability, low cost, and compactness. In contrast, for active Q-switching, the additional mechanisms integrated in the laser cavity will result in a high insertion loss, besides increasing the complexity of the cavity.

Nowadays, graphene has been attaining significant interest and attention for both photonics and optoelectronics applications due to its outstanding and unique features, including high mobility, good optical transparency, and ultra-wideband tunability effected by the linear dispersion of the Dirac electrons [12]. Its zero bandgap energy contributes to the high-bandwidth detection of light. It also affords the benefit of being used as a saturable absorber in broadband lasers due to the facile saturation of its absorption that is triggered by Pauli blocking [13]. In this regard, graphene has emerged as a strong candidate to be employed in the development

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of passively mode-locked [14–20] and Q-switched [8,21–23] fiber lasers due to its unique properties, which meet the important criteria required for a good saturable absorber in terms of saturation intensity, modulation depth, recovery time, optical damage threshold, and wavelength range. Prior to this, the saturable absorber was created using a semiconductor-saturable-absorber-mirror (SESAM) and single-wall carbon nanotubes (SWCNTs) [18,24,25], which unfortunately have several downsides [8,15,16,24].

In this paper, a graphene-based Q-switched erbium-doped fiber laser (EDFL) with a tunable fiber Bragg grating (TFBG) is demonstrated. Generally, most Q-switched fiber lasers use a tunable band-pass filter (TBF) as the tuning mechanism, such as reported in [8,21]. A different approach in providing the tuning mechanism is introduced in our proposed Q-switched EDFL, which is by using a TFBG. The use of a TFBG for tuning the wavelength is more beneficial in that it offers an improvement over the commonly used TBF in terms of achieving a narrower 3 dB transmission bandwidth as well as making the cavity configuration simpler with a lower cost consumption compared to using the TBF. This paper also proposes and presents a new technique for depositing single layer graphene within the fiber laser cavity. With a Q-switched threshold of 39.8 mW, this graphene-based

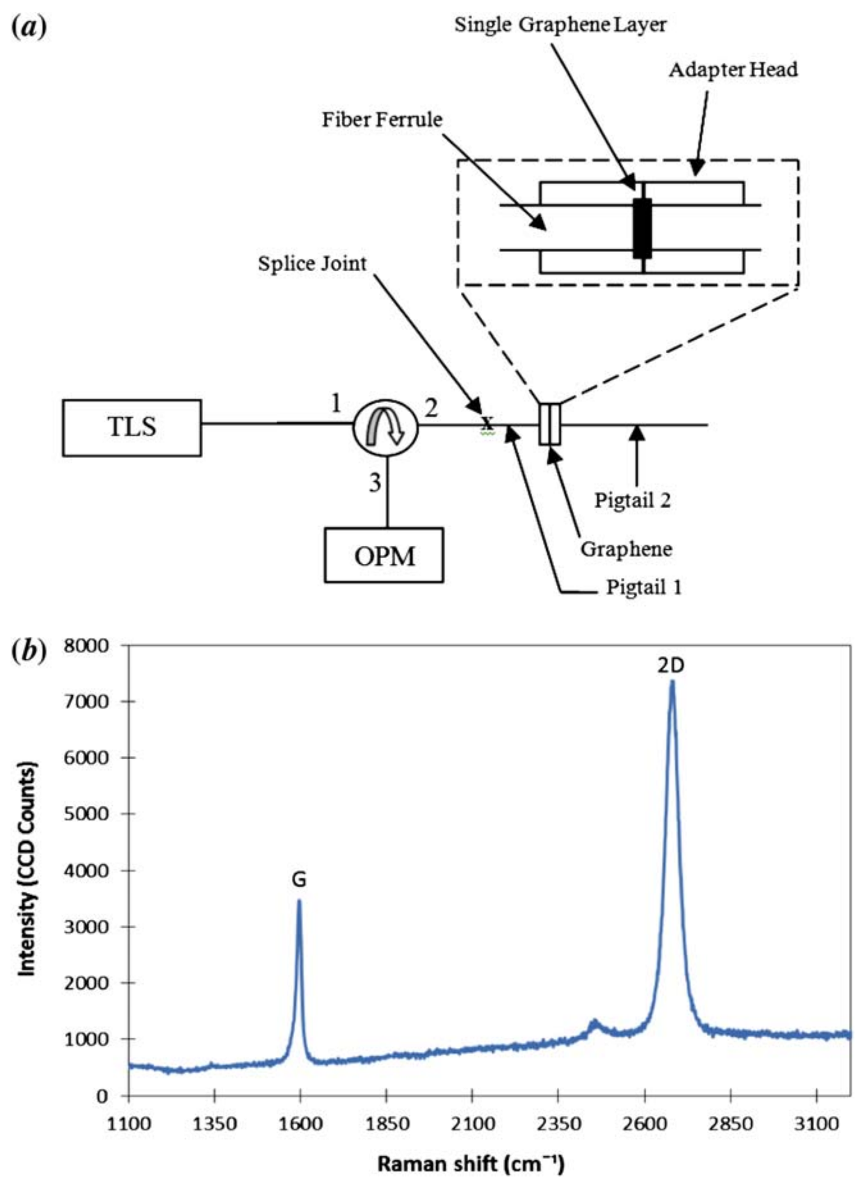

Figure 1. (*a*) Schematic diagram using an optical extraction forming a graphene layer on the fiber end. The inset shows a blown-up view of the adaptor in which the graphene layer is deposited. (*b*) The Raman spectrum of graphene flake. (The color version of this figure is included in the online version of the journal.)

Q-switched EDFL provides a large range of repetition rate, ranging from 1.387 kHz to 208.000 kHz with an exponential increment. To the best of authors' knowledge, this is the first demonstration of a tunable passively graphene-based Q-switched fiber laser with its tunability provided by a TFBG.

2. Deposition of a single layer graphene

In this research, a novel and efficient technique for depositing a single or nearly single layer of graphene within the cavity of the fiber laser is proposed and demonstrated. This technique entails the removal of excess graphene from an optical fiber ferrule that has been dipped in a graphene solution emulsion using a simple method such as a fiber cleaner. A schematic for this method is shown in Figure 1(*a*).

Firstly, a 1 m length of a fiber pigtailed, Pigtail 1, is spliced and connected to port 2 of an optical circulator (OC). The other end of the pigtail, which has the connector, is then submerged into the graphene solution emulsion. The graphene used in this research work was obtained from Graphene Research Ltd. in the form of aqueous solution containing graphene flakes suspended in a *N*-methylpyrrolidone solution. The graphene flakes have an average flake thickness of 0.35 nm with an average particle size of 550 nm. The formation of the graphene layer is done using a 1550 nm light source from a tunable laser source (TLS), operating with an output power at 11 dBm, which has been connected to Port 1 of the OC. After 3 min, the fiber ferrule of Pigtail 1 is removed from the solution and the TLS is turned off. At this point, normally a thick layer of graphene is formed. This ferrule is then connected to the ferrule of another pigtail, Pigtail 2, through a conventional FC/PC adapter. The TLS is then switched on again, and the reflected power of the graphene layer, which is reflected back to Port 2 then travels to Port 3, is measured using an optical power meter (OPM). This is done for 3 min (any other time that is suitable may also be used). During this period of time, a portion of the graphene layer from Connecter 1 will be transferred to Connecter 2. The connector of Pigtail 2 is then removed from the adapter and cleaned slowly using a fiber cleaner so as to not remove the entire graphene layer. The ferrule is then reconnected back to the adapter and the reflected power is measured using the OPM. This process is repeated until the measured reflected power is about 4.1%, taking into account the reflection for a single layer of graphene of ∼0.1% [12] and also Fresnel reflection of ∼4.0%. A typical Raman spectrum of the graphene flake is shown in Figure 1(*b*).

The primary advantage of the proposed method is that it is easier and cheaper to accomplish as compared to the conventional approaches for depositing graphene onto a fiber ferrule, such as sandwiching a graphene–polyvinyl alcohol composite film [19] or graphene–polymer nanocomposite thin-film [16,20,26] between two fiber connectors, spraying a graphene suspension onto the flat surface of a side-polished fiber for evanescent field interaction [14] or transfer using a PMMA foil [11]. The proposed method is also more reliable as compared to the optical deposition technique [18,21,22], requiring a lower laser power and also allows the use of the deposited graphene layer immediately after the deposition process, without any further drying or evaporation

3. Experimental setup

Figure 2 shows the experimental setup of the proposed graphene-based Q-switched erbium-doped fiber laser

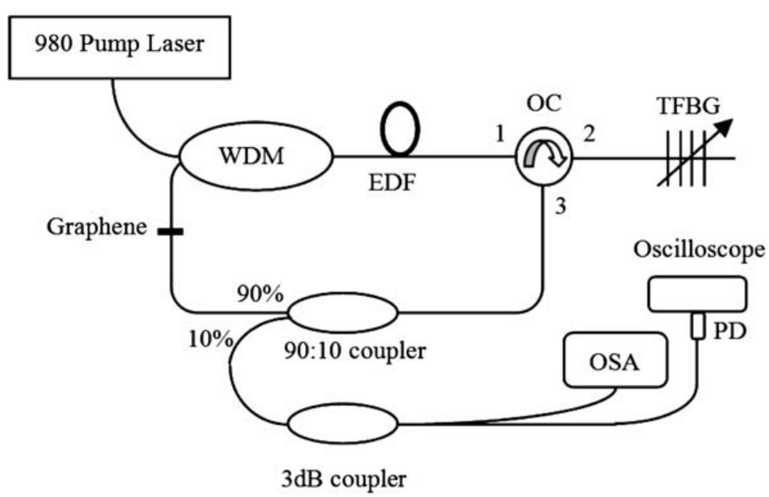

Figure 2. Experimental setup of the proposed graphene-based Q-switched EDFL with a TFBG.

(EDFL) incorporating a TFBG. The setup consists of a 1 m long highly doped erbium-doped fiber (EDF) (Liekkitm Er80-8/125), which has absorption coefficients of 41 and 80 dB m^{-1} at 980 and 1530 nm, respectively, and a mode field diameter of 9.5 μm at 1550 nm. The length of the EDF is chosen such that it gives the optimum gain with the shortest possible EDF length; this is essential to produce short pulses with high pulse energies in the operation of the Q-switched laser [23]. A 980 nm laser diode is used to pump the EDF through and is injected into the cavity through the 980 nm port of a 980/1550 wavelength division multiplexer (WDM). The EDF is connected to the common port of the WDM, with the other end connected to Port 1 of an OC. Port 2 of the OC is connected to the TFBG, which provides the tuning mechanism for the system. The TFBG has a tuning range of more than 10 nm, which is obtained by applying mechanical stress (extension or compression) on a piece of Perspex with a low Young modulus in the upward or downward direction with an FBG glued onto it [27].

The amplified spontaneous emission (ASE) generated from the EDF is filtered at the TFBG, and the signal from the TFBG will travel back to Port 2 of the OC and will be emitted at Port 3, where it now travels to the common port of a 90:10 optical coupler. The 90% port is connected to the graphene sandwiched ferrule, which in turn connects to the 1550 port of the WDM, thereby

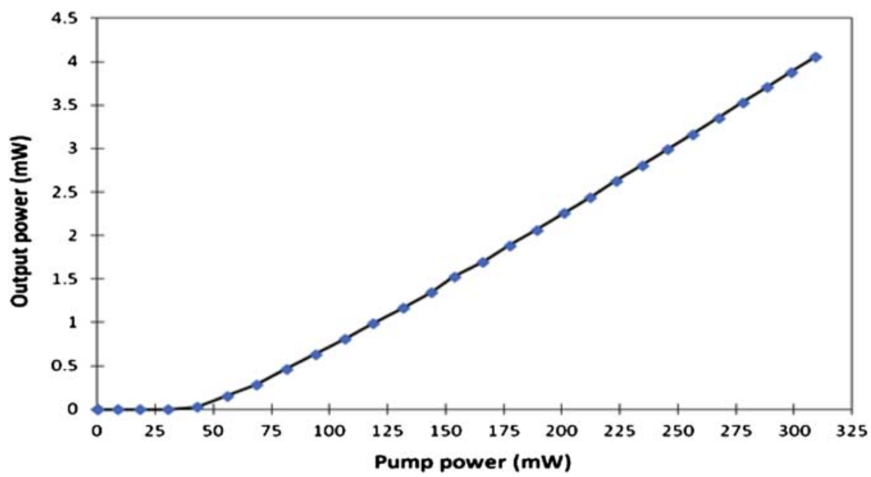

Figure 3. Output power as a function of pump power. (The color version of this figure is included in the online version of the journal.)

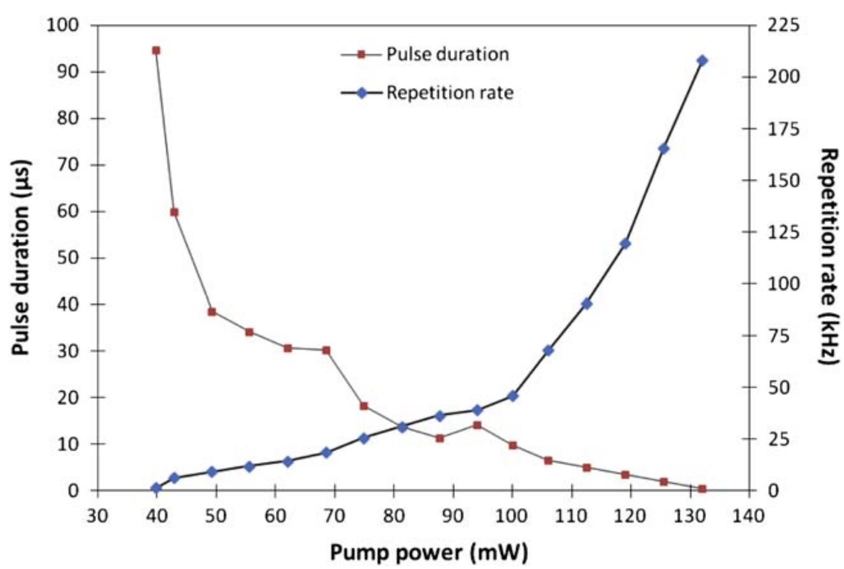

Figure 4. Pulse duration and repetition rate as a function of pump power. (The color version of this figure is included in the online version of the journal.)

completing the cavity. The 10% signal extracted from the cavity is channeled into a 3 dB coupler, where half of the signal is directed into an optical spectrum analyzer (OSA, Yokogawa AQ6317) with a spectral resolution of 0.02 nm for spectral analysis of the Q-switched EDFL. The other half of the sample signal is connected to an Oscilloscope (LeCroy, 352A) via a 6 GHz photodetector (PD, HP Lightwave Detector) and is used to observe the output pulse train of the Q-switched operation in the form of electrical signal.

4. Results and discussion

The relationship between the output power and the pump power for this graphene-based Q-switched EDFL at a wavelength of 1551.66 nm is plotted in Figure 3. After reaching the laser threshold of approximately 39.8 mW, the output power increases linearly from 0.029 mW to 4.055 mW, with respect to the pump power, having a gradient of 0.015. From the plotted graph, it can be observed that until the maximum pump power of 309.0 mW, the output power does not yet reach the saturation value, which is probably due to the high erbium dopant concentration in the gain medium. Therefore, it is predicted that the output power can be further increased by increasing the pump power above 309.0 mW. However, due to the limitation of the pump laser, the output power characteristics for the pump power exceeding 309.0 mW is not demonstrated.

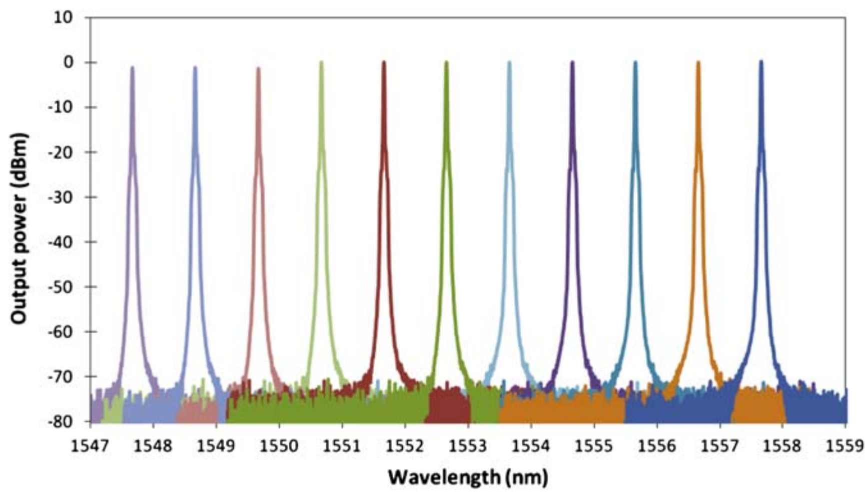

Figure 5. Output spectra of the tunable Q-switched operation for 11 tuned wavelengths. (The color version of this figure is included in the online version of the journal.)

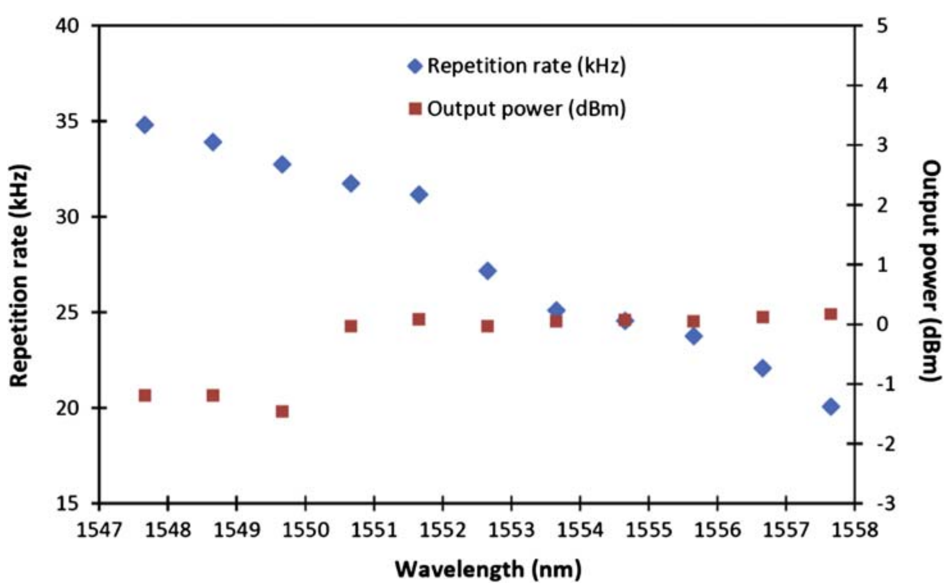

Figure 6. Repetition rate and average output power as a function of wavelength. (The color version of this figure is included in the online version of the journal.)

The change of the pulse duration and the repetition rate with the increased pump power at a wavelength of 1551.66 nm was also investigated, as shown in Figure 4.

As can be seen in Figure 4, the repetition rate as a function of pump power shows an exponential pattern from 1.387 kHz at pump power of 39.8 mW, which is the Q-switching threshold, to a maximum value of 208.000 kHz at pump power of 132.0 mW. This indicates that this graphene-based Q-switched EDFL can provide a significantly wide repetition rate range, which is over 206.613 kHz, tunable from 1.387 kHz to 208.000 kHz. The repetition rate range obtained in this graphene-based Q-switched EDFL is comparable to that previously reported [23]. On the other hand, the pulse duration varies from 94.80 μs at pump power of 39.8 mW to 0.412 μs at pump power of 132.0 mW. Therefore, it can be inferred that the graphene-based Q-switched EDFL is able to produce a short pulse duration, which is as low as 0.412 μs at pump power of only 132.0 mW, and can produce shorter pulse durations at higher pump powers. However, in this work the pump power is restricted to a maximum of 132.0 mW so as to avoid possible damage to the graphene layer and subsequently disrupting the generation of the Q-switched pulses.

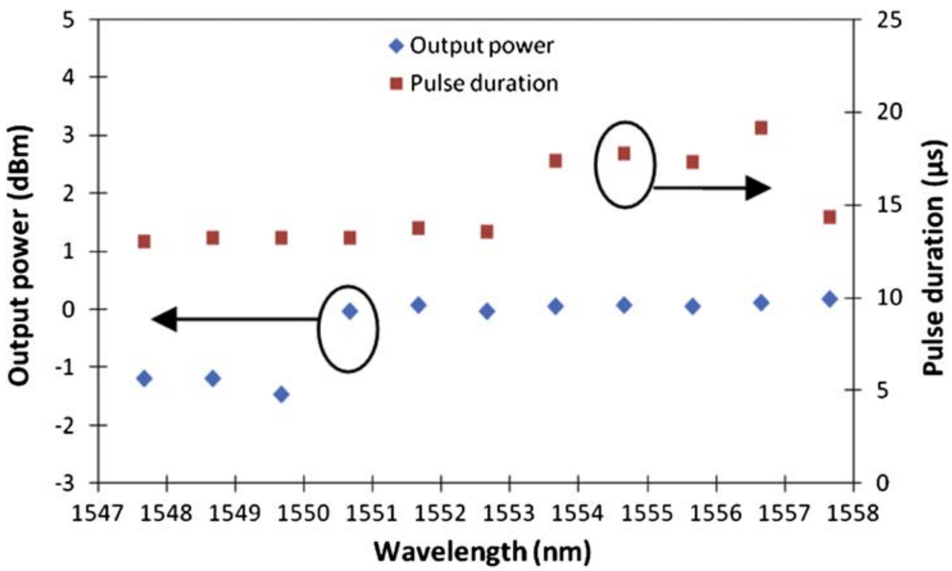

Figure 7. Output power and pulse duration as a function of wavelength. (The color version of this figure is included in the online version of the journal.)

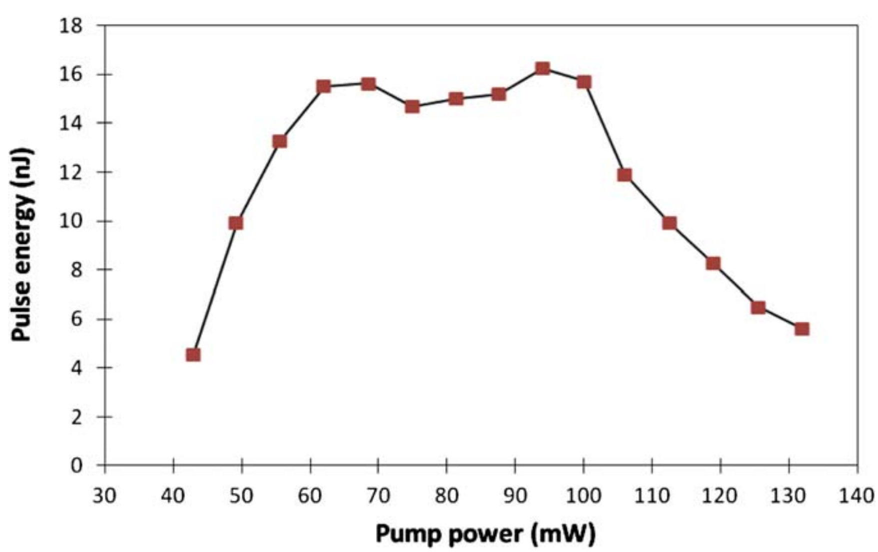

Figure 8. Pulse energy as a function of pump power. (The color version of this figure is included in the online version of the journal.)

Figure 5 shows the output spectra of the wavelength-tunable Q-switched operation taken from the OSA for 11 tuned wavelengths at a fixed pump power of 143 mW. The average 3 dB bandwidth for each output spectrum is approximately 0.0154 nm. The indicated tuning range of this fiber laser covers a wavelength range of 10 nm, which spans from 1547.66 nm to 1557.66 nm, and this is not limited as the tuning range can exceed 10 nm. As the TFBG is tuned manually, the speed at which the wavelength shifts is dependent wholly on the user, which is described in detail in [27].

From Figure 5, it can be seen that there is a very low output power variation over the entire wavelength range, with the power amplitudes ranging from 0.17 to −1.46 dBm. The maximum output power of 0.17 dBm is at the wavelength of 1557.66 nm, varying slightly among all the other wavelengths in the figure.

The variation of the repetition rate and the average output power at different wavelengths from 1547.66 nm to 1557.66 nm by tuning the TFBG, with the pump power fixed at 81.3 mW, were also observed, as shown in Figure 6.

Figure 6 shows that the repetition rate becomes lower as the wavelength is tuned to the longer wavelengths. The highest repetition rate obtained is 34.8 kHz at the wavelength of 1547.66 nm, which decreases gradually across the wavelength range to a value of 20.07 kHz at the wavelength of 1557.77 nm. As reported in [21], the

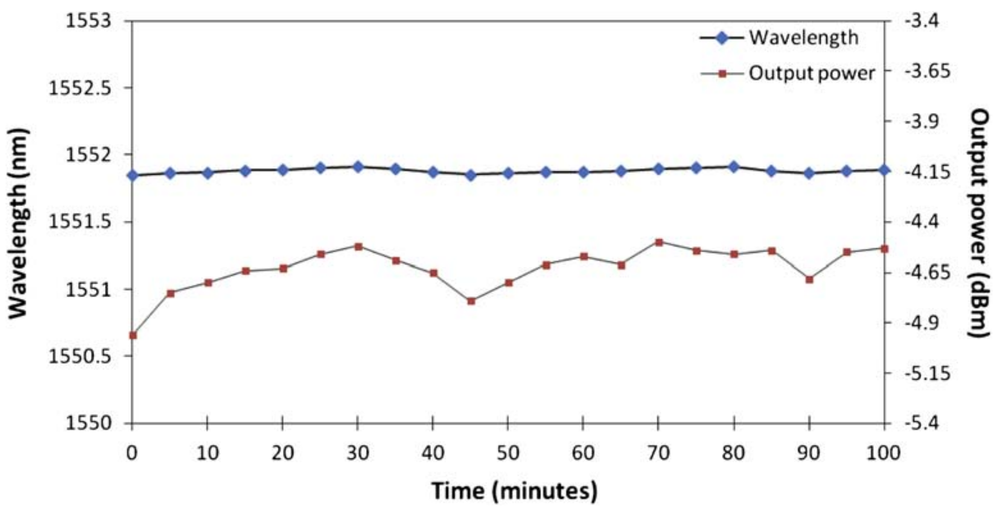

Figure 9. Stability measurement of the output power and wavelength over 100 min observation time. (The color version of this figure is included in the online version of the journal.)

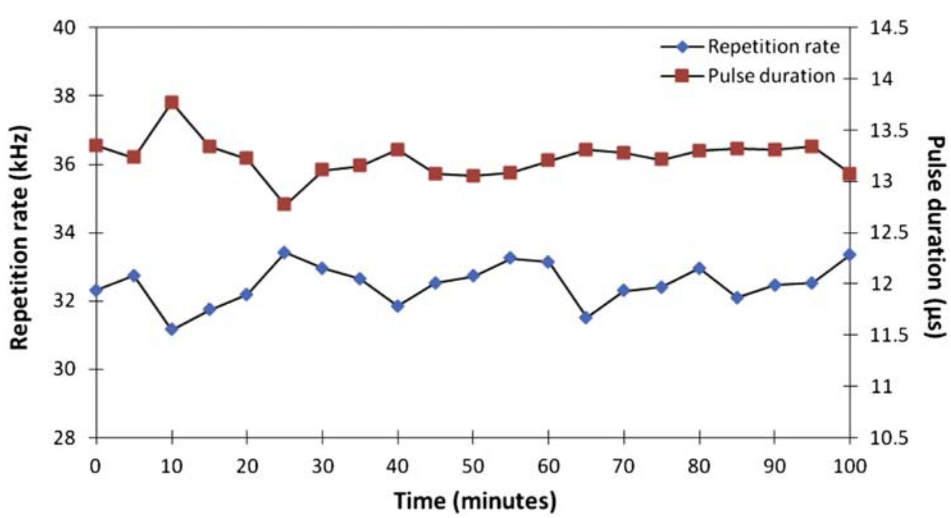

Figure 10. Stability measurement of the repetition rate and pulse duration over 100 min observation time. (The color version of this figure is included in the online version of the journal.)

gain difference of the EDF as well as the insertion loss in the cavity varies with wavelength, which will affect the cavity loss and consequently causes the change in the repetition rate at different wavelengths. The decrease in the repetition rate can also be attributed to the gain spectrum of the laser cavity as well as the saturable absorption characteristics of graphene, which has similar characteristics to carbon nanotubes, as reported in [28]. The average output power on the other hand starts at a lower value of approximately −1.46 dB m within a wavelength range of between 1547 nm and 1550 nm, and subsequently rises to about 0.17 dB m in the wavelength region of between 1551 nm and 1558 nm. The average power is a product of the repetition rate, peak power and pulse duration, and this implies that as the repetition rate decreases, there will be an increase in the pulse duration, thereby making the average output power constant, as is observed in Figure 6.

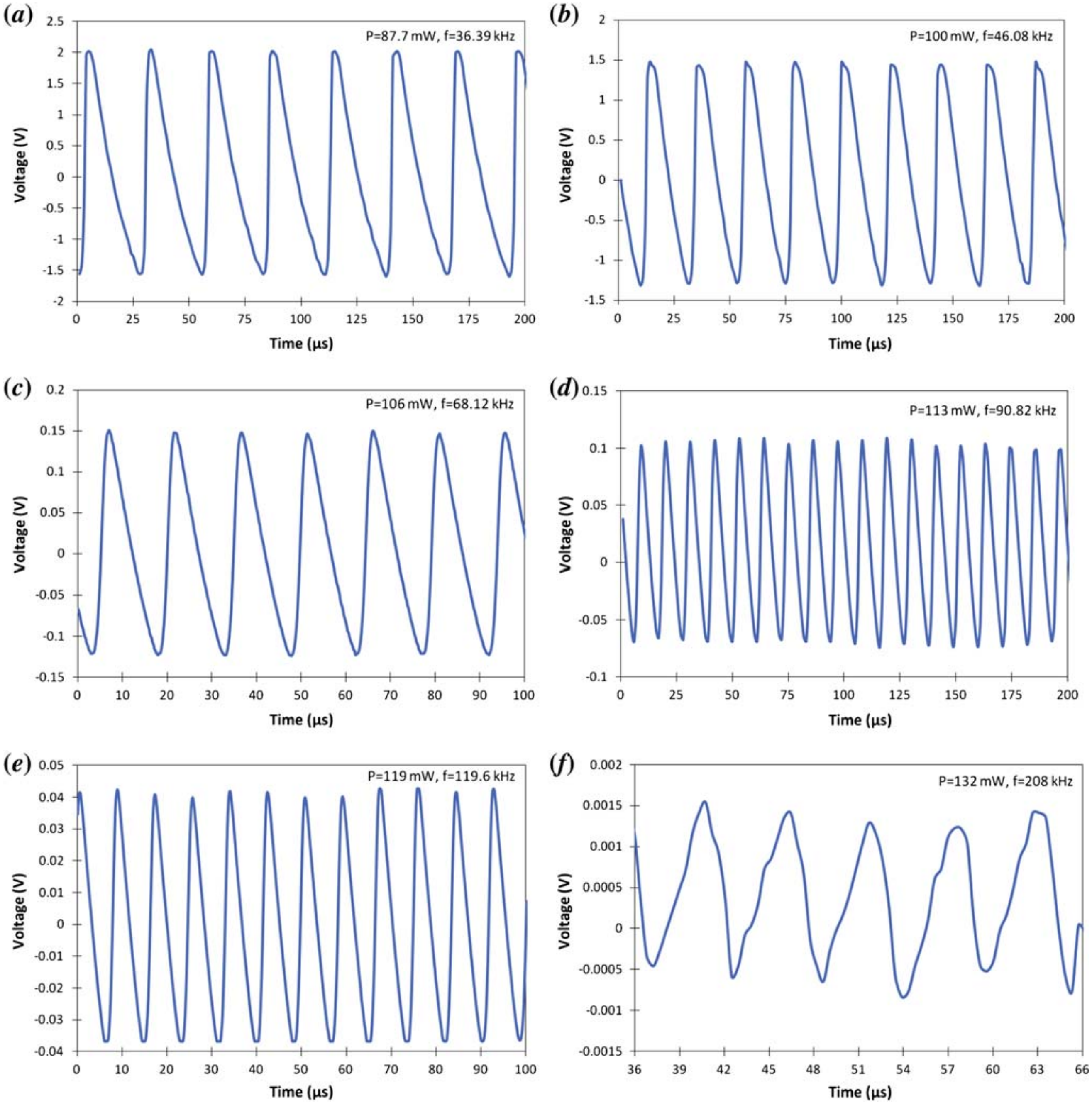

Figure 11. Typical output pulse train of the Q-switched operation under different pump power: (*a*) 87.7 mW, (*b*) 100 mW, (*c*) 106 mW, (*d*) 113 mW, (*e*) 119 mW, (*f*) 132 mW. (The color version of this figure is included in the online version of the journal.)

Figure 7 shows the output power and the pulse duration measured against the tuned wavelength at the pump power of 143.0 mW and 81.3 mW, respectively.

At a wavelength of 1550.66 nm and above, only slight variation of the output power is observed with an average value of around 0.1 dB m. However, at shorter wavelengths, i.e. below 1550 nm, the output power slightly drops to an average value of around −1.3 dB m. On the other hand, the pulse duration is relatively shorter at this wavelength range, which is about 13 μs as compared to between 17 μs to 19 μs at the longer wavelengths.

An additional characterization for this Q-switched laser operation, which involves the pulse energy as a function of pump power, was also investigated at the wavelength of 1551.66 nm and the result is shown in Figure 8.

From Figure 8, it can be observed that the pulse energy increases from 4.56 nJ at pump power of 42.9 mW to 15.51 nJ at pump power of 62.1 mW. After 62.1 mW, the pulse energy shows some small variations until 100.0 mW, whereby it then decreases gradually to 5.61 nJ at pump power of 132.0 mW. The highest pulse energy obtained is at 94.0 mW, which is 16.26 nJ.

To investigate and verify the stability of the output power and output wavelength in the proposed graphene-based Q-switched EDFL, a short-term stability measurement was carried out at a pump power of 62.1 mW and the result is shown in Figure 9. The observation time is over 100 min at 1551.66 nm with an output power of −4.96 dB m initially. The power and wavelength variation are observed to be less than 0.47 dB m and 0.067 nm, respectively. This proves that the output stability of the proposed graphene-based Q-switched EDFL is well maintained over time.

In addition, the stability of the repetition rate and pulse duration for the proposed graphene-based Q-switched EDFL was measured over 100 min observation time at a wavelength of 1551.66 nm, with the pump power fixed at 81.3 mW. Figure 10 shows the stability measurement of the repetition rate and pulse duration within a time interval of 5 min. The repetition rate and the pulse duration vary slightly with time, with a maximum variation of 2.26 kHz and 1.0 μs, respectively.

By changing the pump power, it is possible to observe the variation of the output pulse train of the Q-switched operation measured by the oscilloscope via the 6 GHz photodetector; the traces of the output pulse train are shown in Figure 11.

As illustrated in Figure 11, the pulse train for every different pump power exhibits a smooth, clean, and uniform pulse shape. This verifies that the pulse train of the Q-switched operation is free from self-mode locking effects and pulse jitter effects, except that at the pump power of 132 mW with a repetition rate of 208 kHz, the pulse train is slightly unstable, being a little bit unbalanced and with an asymmetrical pulse shape. The example of single pulse envelope of the pulse train with a repetition rate of 90.64 kHz at 113 mW of pumping power is illustrated in Figure 12, having a pulse duration of 5.26 μs.

Apart from pulse repetition rate, pulse duration, and pulse energy, the pulse peak power for this graphene-based Q-switched EDFL has also been characterized with respect to the change of the pump power and the tuned wavelength. The graphs of the peak power as a

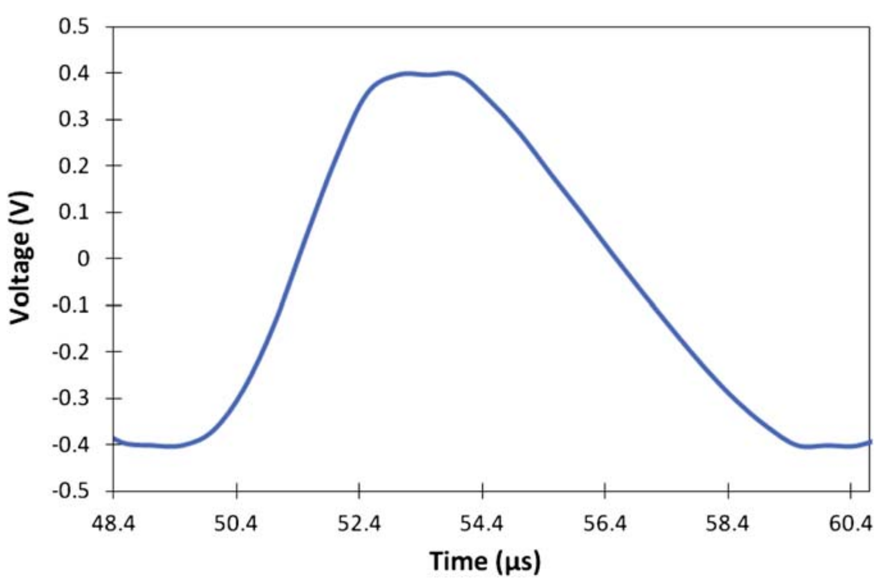

Figure 12. Single pulse envelop at 113 mW of pumping power. (The color version of this figure is included in the online version of the journal.)

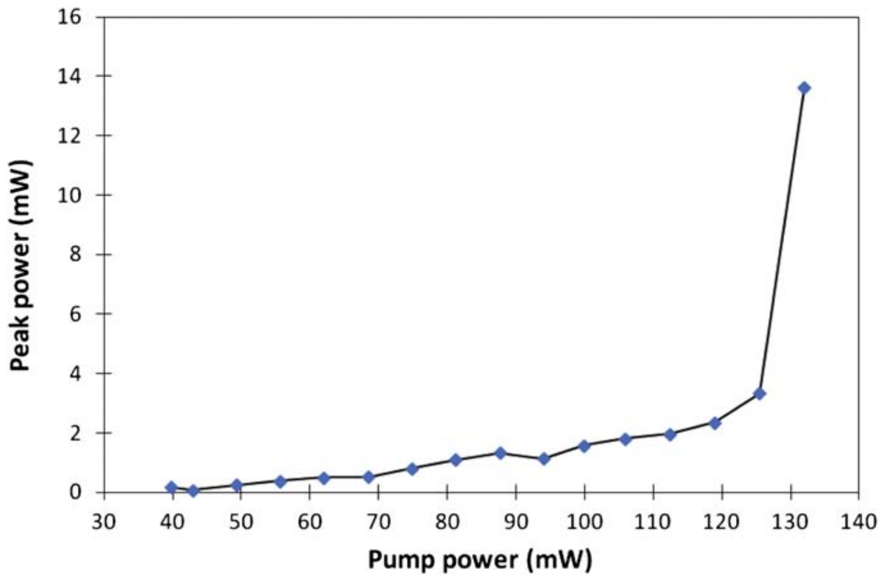

Figure 13. Peak power as a function of pump power. (The color version of this figure is included in the online version of the journal.)

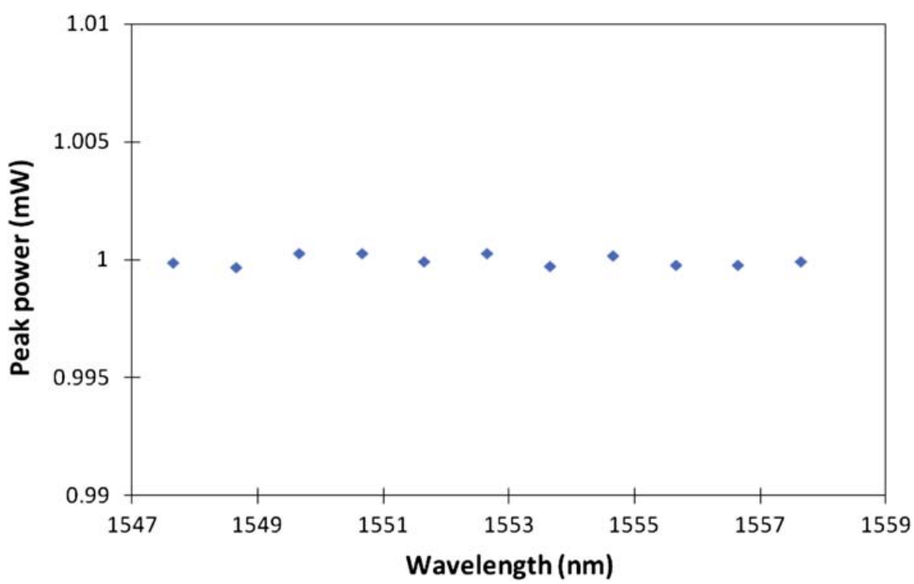

Figure 14. Peak power as a function of wavelength. (The color version of this figure is included in the online version of the journal.)

function of pump power and wavelength are plotted in Figures 13 and 14, respectively.

The peak power increases from 0.16 mW to 13.61 mW as the pump power is increased from 39.8 mW to 132.0 mW, which can be observed in Figure 13. For the plot of peak power against wavelength shown in Figure 14, the peak power has an almost constant value of about 1 mW across the 10 nm wavelength tuning range, from 1547.66 to 1557.66, at a fixed pump power of 81.3 mW, having a variation of less than 0.0006 mW.

5. Conclusion

A tunable graphene-based Q-switched EDFL with a TFBG is proposed and demonstrated. The proposed setup uses a novel ferrule-to-ferrule transfer technique to obtain a single graphene layer for Q-switch operation, while a TFBG acts as a wavelength tuning mechanism. The threshold pump power of the EDFL is approximately 39.8 mW, with a saturation point above the maximum pump power of 309.0 mW. The EDFL can provide a significantly wide repetition rate range of over

206.613 kHz and is tunable from 1.387 kHz to 208.000 kHz, as well as a varying pulse duration of 94.80 μs at a pump power of 39.8 mW to 0.412 μs at 132.0 mW. The laser output of the system covers a wavelength range of 10 nm from 1547.66 nm to 1557.66 nm, with peak powers of 0.17 to −1.46 dB m. As the output wavelength shifts towards the longer wavelength region, the repetition rate of the EDFL decreases from 34.8 kHz at 1547.66 nm to 20.07 kHz at 1557.77 nm, while the pulse energy increases from 13.45nJ to 23.32nJ. The pulse duration is relatively lower at the shorter wavelength region, with an average value of 13 μs at wavelengths less than 1553 nm. The pulse energy also changes with respects to the pump power, varying from 4.56 nJ at a pump power of 42.9 mW to 5.61 nJ at 132.0 mW, with the highest pulse energy of 16.26 nJ obtained at a pump power of 94.0 mW. The system is stable, with minimal variations in power and wavelength of less than 0.47 dB m and 0.067 nm respectively observed over a 100 minute period, as well as repetition rate and the pulse duration variations of 2.26 kHz and 1.0 μs respectively over the same period. The output pulse train observed from the 6 GHz photodetector and oscilloscope show a smooth, clean and uniform pulse shape, thereby verifying that the Q-switched operation is free from self-mode locking and pulse jitters. The pulse peak power peak power increases from 0.16 mW to 13.61 mW for pump powers of 39.8 mW to 132.0 mW, with variations of less than 0.0006 mW over 10 nm wavelength tuning range. To the knowledge of the authors, this is the first demonstration of a Q-switched graphene-based EDFL using a TFBG as a tuning mechanism.

Acknowledgements

We would like to thank the University of Malaya for providing the HIR Grant (Terahertz, UM.C/HIR/MOHE/SC/01), MOHE, for funding this project.

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