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Tunable Q-switched erbium doped fiber laser with graphene oxide paper based saturable absorber

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We demonstrate a tunable wavelength Q-switched erbium doped fiber laser (EDFL) using a graphene oxide (GO) saturable absorber (SA). The GO solution was prepared using the simplified Hummer's method, which is then thinly spread into a petri-disk to make a paper-like material. The GO paper is sandwiched between two FC/PC fiber connectors and incorporated into a ring EDFL's cavity for Q-switching operation. The wavelength tunable operation of the Q-switched laser was obtained with a band-pass filter. The stable Q-switched pulse with a tunable range from 1536 nm to 1563 nm was achieved, covering a wavelength range over ~28 nm. The Q-switched EDFL produced maximum pulse energy of 151 nJ at pump power of 80 mW.

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Keywords: Tunable-wavelength, Passively Q-switched laser, Graphene oxide paper

1. Introduction

Q-switched erbium-doped fiber lasers (EDFLs) have attracted intensive attention due to their potential applications in metrology, fiber sensor, optical communication, medical diagnostics, etc [1, 2]. Q-switching is one of the techniques that enable pulsed lasers, which is based on a modulation of the quality factor, Q, of a laser cavity [3]. In Q-switching, the active medium is pumped while lasing is initially prevented by a low Q factor. The stored energy is released in a pulse with duration from μs to ns when lasing is allowed by a high Q factor [3]. Compared to actively Q-switched fiber lasers, passively Q-switched EDFLs have the advantages of compactness, low cost, flexibility and simplicity of design. Different kinds of saturable absorbers (SAs) have been used to realize passive Q-switched pulses, such as the transition metal-doped crystals [1] and semiconductor quantum-well structures [2]. However, these SAs require additional alignment devices, such as lens, mirrors or U-bench units when used in a laser cavity. These devices may introduce extra insertion loss and added complexity. Presently, carbon nanotubes (CNTs) are usually used to achieve Q-switching [4]. However, CNTs have a low damage threshold, and tend to have a bundled entangled morphology.

Graphene based SAs have also gained enormous research interest in recent years due to their advantages, such as continuous and independent wavelength broadband saturable absorption [5, 6], ultra-short recovery time [7], relatively high damage threshold [8], low saturable absorption intensity and large modulation depth [9]. Furthermore, graphene has a low-cost fabrication process, flexible, and can be well compatible with fibers. Besides, graphene oxide (GO) has been also proved to be the promising saturable absorption material for the pulsed fiber laser. In comparison with graphene, GO displays some different properties due to the presence of functional groups, which is absence in graphene and makes it difficult to be processed [10]. In addition, GO shows several advantages compared with graphene, such as the GO can be fabricated by the modified Hummer's method which has the advantages of low cost and mass producing, avoiding the use of any expensive or sophisticated technique [11, 12, 13]. Most studies have been reported on GO based SAs for mode-locked and Q-switched fiber lasers and impressive results have been obtained [14, 15].

To date, there are only few reported works on GO used as a broadband SA within the laser cavity to realize laser tunable over a wide wavelength range. For instance, Ahmad et al. have demonstrated a tunable wavelength Q-switched Bismuth-based EDFL with wavelength tunable range from 1550 nm to 1563 nm with pulse energy of 4.3 nJ [16]. In this paper, tunable wavelength Q-switched EDFL is demonstrated using graphene oxide based SA. The broadband absorption of GO SA enable stable Q-switched pulse to be continuously tuned with the range from 1536 nm to 1563 nm, covering a wavelength range over ~28 nm, limited by our tunable band-pass filter, not graphene oxide itself. The Q-switched EDFL produces maximum pulse energy of 151 nJ. The novelty of this paper is contributed mainly by its tunable operation and the simple method in preparing the SA.

2. Preparation of graphene oxide saturable absorber

At first, the oxidation of graphite flakes was carried out by slowly mixing 320 mL of sulfuric acid (H_2SO_4), 80 mL of phosphoric acid (H_3PO_4), graphite flakes and 18 g of potassium permanganate ($KMnO_4$), by using a magnetic stirrer. The mixture was left for stirring for 3 days to allow the oxidation of graphite. In the process, the color of the mixture changes from dark purplish green to dark brown. Later, hydrogen peroxide (H_2O_2) solution was added to stop the oxidation process, and the color of the mixture changes to bright yellow, indicating a high oxidation level of graphite. The graphite oxide formed was washed three times with 1 M and repeatedly with deionized water until a pH of 4–5 was achieved. The washing process was carried out using simple decantation of supernatant via a centrifugation technique. During the washing process with deionized (DI) water, the graphite oxide experienced exfoliation, which resulted in the thickening of the graphene solution, forming a GO gel. The GO gel was then mixed with DI water to obtain graphene oxide flakes solution. The detail method on the preparation of GO flakes solution was described in reference [13]. This method has the advantage of spending much shorter time in mixing the reactants. Furthermore, the whole process can be carried out without any temperature control.

The graphene oxide solution was thinly spreaded into a petry disk and left for 15 hours to make a paper-like material. A free-standing graphene oxide paper (GOP) is obtained after drying. The fiber-type SA device was constructed by inserting a piece of GOP in between two ferrules. Raman spectroscopy is performed to confirm the presence of graphene layer on the surface of GOP by using laser excitation at 514 nm with an exposure power of 10 mW. The detector is a charge-coupled device (CCD) camera. Fig. 1 shows the measured Raman spectrum with two similar prominent peaks within the Raman shift of 100 to 3200 cm^{-1}. The Raman spectrum reveals two prominent peaks at 1351.5 cm^{-1} and 1586.9 cm^{-1}, which are referred to D and G band, respectively. The G band contributes to an E_{2g} mode of graphite and is related to the in-plane vibration of the sp^2-bonded carbon atoms, whereas the D band is associated with the vibrations of the carbon atoms with sp^3 electronic configuration of disordered graphite. The intensity ratio of D and G bands of the GOP is about 0.997 which indicates the defect levels of sample. The amount of the structural defects for both areas is not large since the D peak is not too broad. In addition, slightly weak of D peak indicates a low density of defects and high crystallinity of the graphene [17]. The 2D peak is also observed at around 2700 cm^{-1} as shown in Fig. 1. This is a second order Raman process originating from the in-plane breathing-like mode of the carbon rings. The number of graphene layers can also be identified based on the width of the 2D peak. By launching the tunable laser source and white light source, the insertion loss of the SA is measured to be around 2.6 dB at 1557 nm.

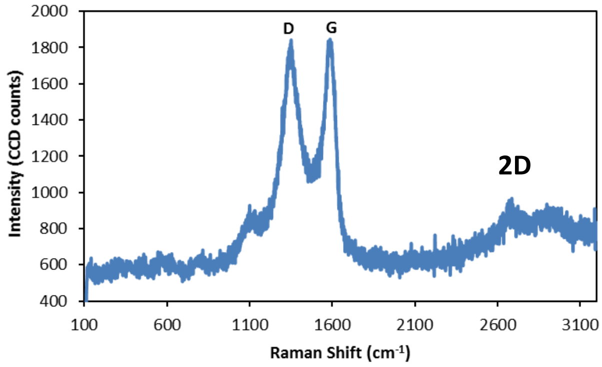

Fig. 1. Raman spectrum of the fabricated GO SA

3. Experimental setup

Fig. 2 shows the experimental setup of the tunable wavelength Q-switched EDFL using the fabricated SA as the Q-switcher. The SA is fabricated and sandwiched between two FC/PC fiber connectors, after depositing index-matching gel onto the fiber ends. The ring EDFL uses a 3 m long Erbium-doped fiber (EDF) with core and cladding diameters of 4 µm and 125 µm respectively, a numerical aperture of 0.16 and Erbium ion absorption of 23 dB/m at 980 nm. The other part of the ring cavity uses a 11 m long standard single mode fiber (SMF-28) with a dispersion of 17 ps/nm km at λ = 1550 nm. It is pumped by a 980 nm laser diode (LD) via a 980/1550 nm wavelength division multiplexer (WDM). An isolator is used in the laser setup to avoid backward reflection and ensure unidirectional propagation of the oscillating laser. As mentioned above, we choose a GO SA to obtain the Q-switched pulse. The output laser is tapped via a 95/5 coupler which keeps 5% of the light oscillating in the ring cavity. The tunable band-pass filter is used to tune the wavelength in the range of ~28 nm. The cavity length is measured to be approximately 14 m. The optical spectrum analyzer (OSA) with a spectral resolution of 0.07 nm is used for the spectral analysis of the wavelength Q-switched laser and an oscilloscope (OSC) is used to analyze the output pulse train of the Q-switching operation via a photo-detector.

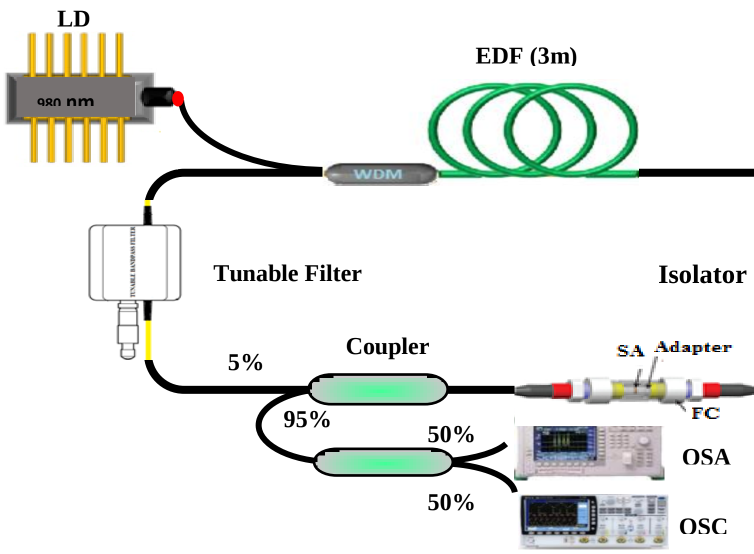

Fig. 2. Experimental setup of the tunable wavelength Q-switched EDFL configured with GO SA

4. Results and discussion

At first, the performance of the ring EDFL was investigated by varying the 980 nm pump power. Initially, the threshold of continuous-wave (CW) operation of the laser was observed at pump power of 50 mW. The laser transited to stable Q-switched operation when the pump power was adjusted over threshold of 55 mW. The output spectrum was tuned from 1536 to 1563 nm by using tunable band-pass filter. This was comparable to the 35 nm range reported for Q-switched tunable wavelength using an unbalanced Mach–Zehnder interferometer [18]. The tuning range was limited by the filter not the SA. Fig. 3 shows the output spectra of the four wavelengths at 1536 nm, 1547 nm, 1555 nm, and 1563 nm with a full-width at half-maximum (FWHM) bandwidth of 0.33 nm at pump power of 80 mW. Without tunable filter the laser exhibits Q-switched pulse at 1558 nm. In order to avoid a passive mode-locking, it is worth noting that we intentionally use a 95/5 coupler, which allow only 5% of the light to oscillate in the cavity. This induces a cavity loss of more than 15 dB in the laser cavity, which is sufficient enough to avoid mode-locking.

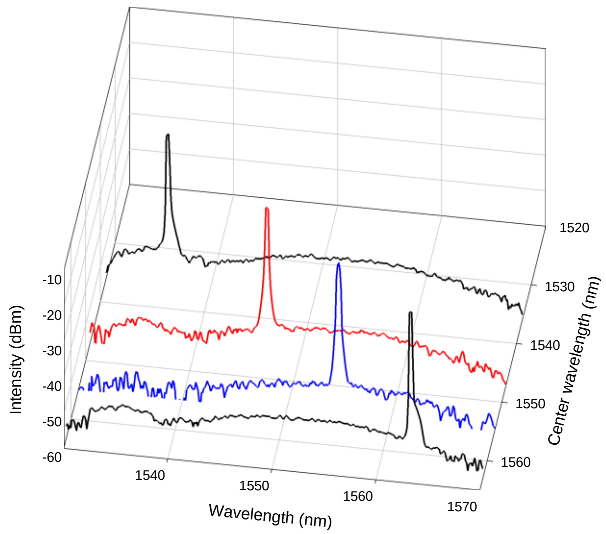

Fig. 3. Optical spectra of the tunable wavelength Q-switched operation

Fig. 4 shows the oscilloscope trace of the Q-switched pulse at pump power of 80 mW by tunable wavelengths of 1536 nm, 1547 nm, 1555 nm and 1563 nm with pulse duration of 41.2 µs, 41.4 µs, 39.7 µs and 52.3 µs respectively. It is observed that the Q-switched operation is stable for all tunable wavelengths. It is observed that in the absence of GO SA, the Q-switched pulses disappears which indicates that the Q-switching is due to GO SA rather than to self-Q-switching.

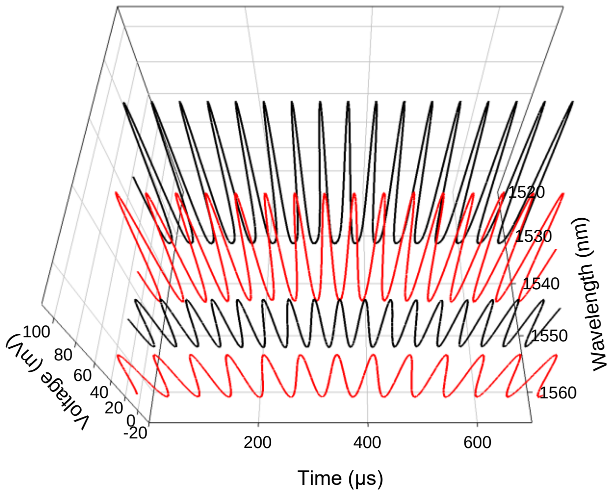

Fig. 4. Typical output pulse train of Q-switched operation with the tunable filter at 1536 nm, 1547 nm, 1555 nm and 1563 nm

Fig. 5 shows how repetition rate and pulse width are related to the function of pump power for Q-switched lasers at wavelength of 1536 nm and 1555 nm. The pulse repetition rate is seen to increase almost linearly with the pump power, while the pulse width decreases almost linearly with the pump power. This agrees well with the theory of passive Q-switching with saturable absorber. The pulse repetition rate at wavelength of 1536 nm can be tuned from 11.78 kHz to 24.48 kHz by varying the pump power from 55 mW to 80 mW. On the other hand, the pulse width reduces from 25.67 μs to 11.55 μs. The Q-switching pulse disappears as the pump power is increased above 80 mW. In the meantime, the repetition rate at wavelength of 1555 nm increases from 11.5 kHz to 25.36 kHz while its pulse width decreases from 28 μs to 18.22 μs as the pump power increases from 55 mW to 80 mW.

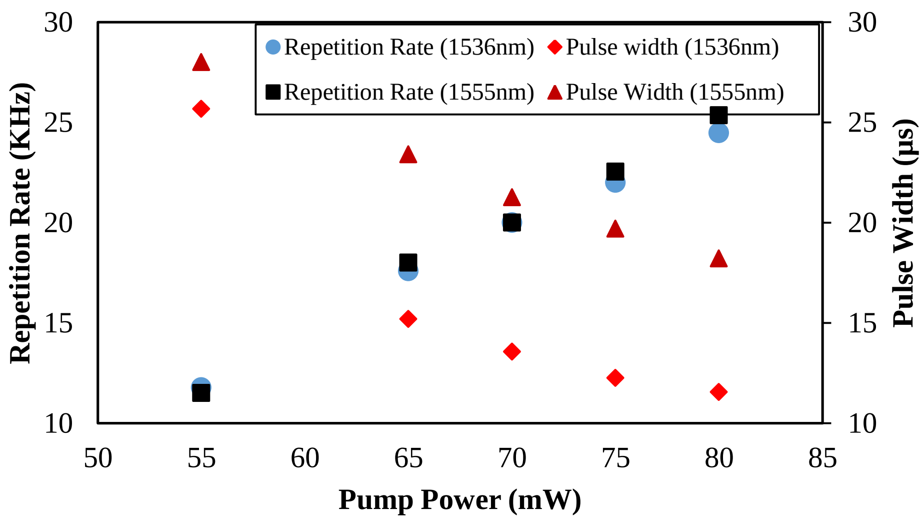

Fig. 5. Repetition rate and pulse width as functions of pump power with the tunable filter at 1536 nm and 1555nm

The average output power and pulse energy of the Q-switched as functions of pump power are shown in Fig. 6. As shown in the figure, the output power for laser at both wavelengths increases almost linearly with increment of the pump power. The output power for b9.oth wavelengths of 1536 nm and 1555 nm increases from 1.2 mW to 3.7 mW as the pump power varies from 55 mW to 80 mW. In the meantime, the pulse energy increases from 102 nJ to 151 nJ and from 104 nJ to 146 nJ for wavelengths of 1536 nm and 1555 nm respectively. The maximum pulse energy of 151 nJ is obtained at pump power of 80 mW, which is much higher than 36.9 nJ thus far achieved for tunable-wavelengths, Q-switched pulse laser based on graphene SA [16]. Fig. 7 shows the radio frequency (RF) spectrum of Q-switched EDFL obtained using RF spectrum analyzer via a 1.2 GHz photo-detector. In the experiment, the pump power was fixed at 80 mW while the operating wavelength is set at 1536 nm. As shown in the figure, the repetition rate of 24.48 KHz is obtained with the corresponding signal to noise ratio (SNR) of around 53 dB. This confirms the pulse stability of the Q-switched laser.

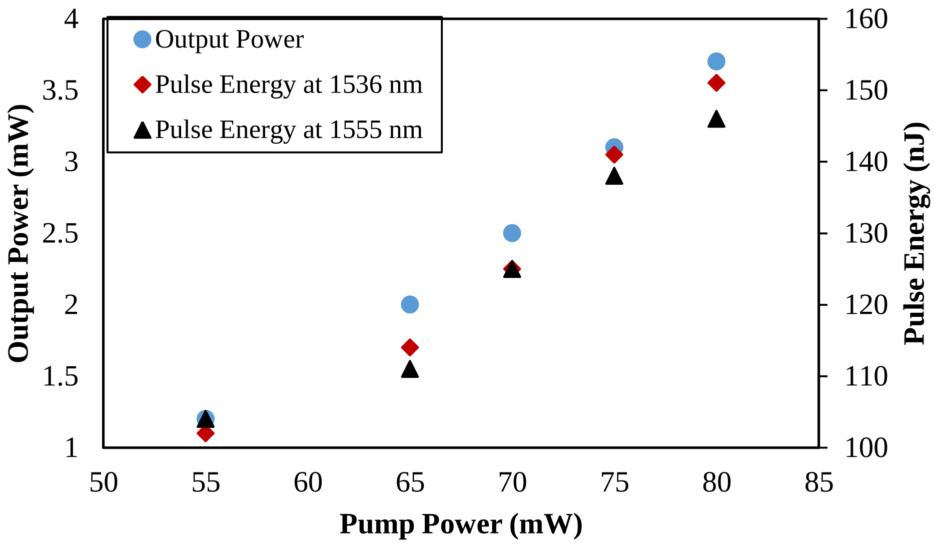

Fig. 6. Average output power and pulse energy as functions of pump power for Q-switched at wavelength of 1536 nm and 1555nm

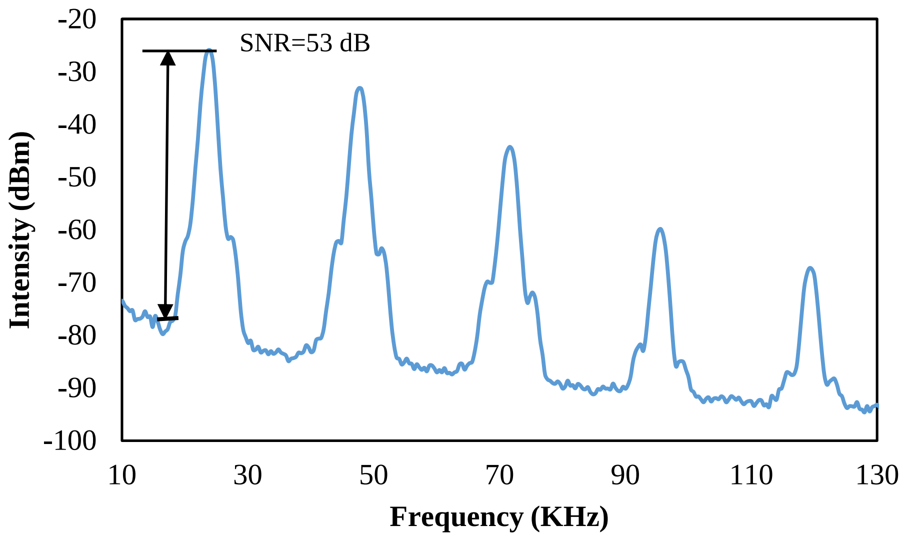

Fig. 7. RF spectrum of the Q-switched EDFL at pump power of 80 mW and wavelength of 1536 nm

5. Conclusion

We have experimentally demonstrated tunable wavelength Q-switched EDFL based on GO SA. The laser makes use of a GO SA to generate a stable Q-switched fiber laser operating in tunable wavelength at 1536 nm, 1547 nm, 1555 nm and 1563 nm. Inserting a tunable filter into the cavity makes it possible to tune the wavelength in the range of ~28 nm. The maximum pulse energy of the Q-switched EDFLs is 151 nJ. Besides showing good tunable wavelength Q-switching performance, the GO SA is easy to fabricate and cheap. This makes the proposed EDFL to be low cost and simple, which is suitable for applications in metrology, optical communication, environmental sensing, and biomedical.

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