

Q-switched Zirconia-Yttria-Aluminium-Erbium-doped pulsed fiber laser with a pencil-core of graphene as saturable absorber

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A flexible and controllable Q-switched using Zirconia-Yttria-Aluminium-Erbium-doped silica fibre as an active gain medium with pencil-core of graphene as saturable absorber (SA) was demonstrated. The zirconia fibre was fabricated using the modified chemical vapour deposition (MCVD) method, whereas the SA was fabricated using a simple and fast preparation of mechanical exfoliation technique from a pencil core of graphene material. At a maximum pump power of 121.5 mW, the repetition rate, pulse duration, signal-to-noise ratio and pulsed energy were 20 kHz, 0.011 μ s, 56 dB and 78.1 nJ, respectively.

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1. Introduction

An efficient, compact and cost-effective Q-switched pulsed fibre laser is in extraordinary demand in numerous contexts and especially in biomedical applications such as sensing, tattoos removal, laser surgery, skin and face treatment, plastic surgery and laser dentistry [1-4]. Although researchers are fascinated with ultrafast pulsed fibre laser and ultrashort mode-locked pulse duration, the Q-switched fibre laser has steadily established advantages due to its stability, flexibility repetition rate and pulse duration, and high pulsed energy [5-7]. Moreover, a Q-switched pulsed laser is easier to develop due to the difficulty of balancing the equilibrium between dispersion and nonlinearity as compulsory to achieve the mode-locked operation [8]. There has been a tremendous amount of research into alternative saturable absorber (SA) materials based on Q-factor to develop a passive Q-switched pulsed fibre laser by implanting the SA into cavity laser arrangement.

In past years, novel SAs based on carbon nanotubes (CNTs) and graphene have been explored extensively [9-10]. Nonetheless, CNTs has constrained on its operating wavelength of the pulsed laser, which is dependent on the diameter of nanotubes. Meanwhile, graphene has certain

boundaries such as the zero bandgap and low modulation depth as an SA candidate [11]. However, this zero-bandgap energy offers a wide wavelength operational region to transmit almost 97.7 % incident of light, thus provides high optical gain and easily to create pulsed fibre laser. The low modulation depth offers security to control or prevent Pauli blocking, which occurs in many unstable Q-switching lasers that suddenly change to a mode-locking laser. The simplest method to produce graphene is by exfoliating bulk graphite using conservative method of mechanical cleavage. A Q-switched fibre laser using a bulk graphite from a pencil-core as its SA was reported using Thulium-doped fibre (TDF) in the 2-micron region [12]. The laser offers stability with sufficient pulse width and repetition rate, but suffers from low output power and pulsed energy. Additionally, the usage of a long gain medium of 5 meters and consequently a long laser arrangement leads to the problems stated previously.

A homemade Zirconia-Yttria-Aluminium-Erbium-doped (Zr-Y-Al-Er) fibre was engaged as an active medium and the details of its fabrication were reported [13]. The ZrO₂, Y₂O₃, Al₂O₃, and Er₂O₃ doping was successful in enhancing the population emission of Erbium ion concentrations inside the fibre without clustering and quenching possessions. In this paper, we demonstrate a Q-

switched pulsed fibre laser using the same pencil-core of graphene as the SA and as short as 1 meter of Zr-Y-Al-Er-doped fibre as the active medium.

2. Fabrication of Saturable Absorber (SA)

Fig. 1 shows the conservative mechanical exfoliation method used to create the SA. At first, flakes of pencil-core were desquamated on the adhesive surface of transparent tape using a blade. Then, the adhesive tape was folded repeatedly until the flakes were deposited consistently to grow a graphite fragment. The graphene material was obtained from a 2B-grade pencil-core where the graphite was blended with a clay binder. Finally, a small area of $2.5 \times 6 \text{ cm}^2$ from the consistent graphene of pencil-core on the surface of adhesive tape was cut and engaged to a surface of a fibre ferrule with a holding agent.

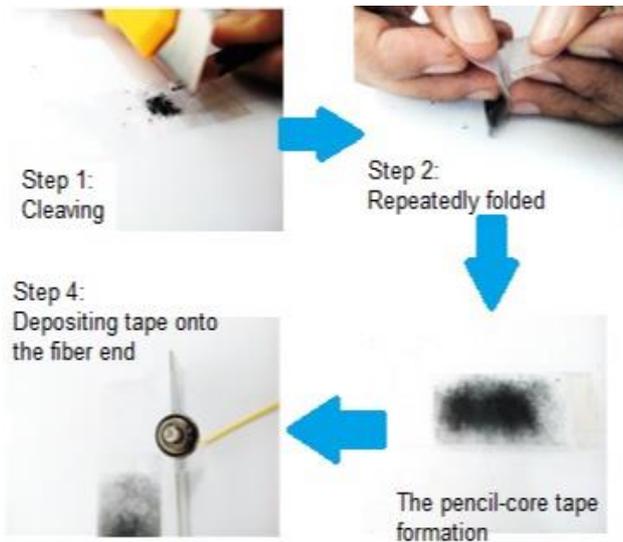


Fig 1. Simple fabrication process of pencil-core tape

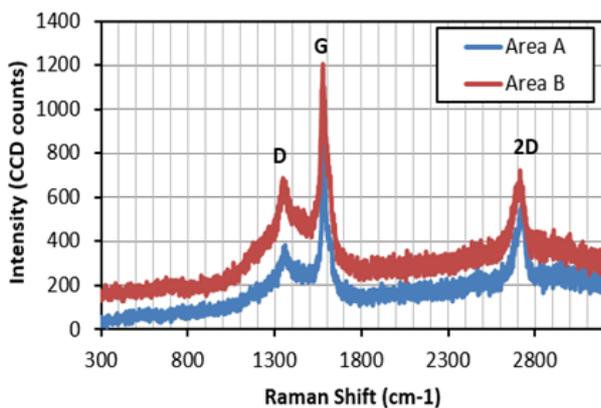


Fig. 2. Pencil-core based on Raman Spectrum (color online)

Fig. 2 illustrates the measured Raman spectrum using Raman spectroscopy (Renishaw, Raman microscope) in two regions A and B with contrasting intensity and three comparable peaks at the range of 100 to 3200 cm^{-1} of Raman shift. The three values were D, G and 2D, with D at 1347.34 cm^{-1} , G at 1577.76 cm^{-1} and 2D at 2707.23 cm^{-1} , defining the pencil-core of graphene layer. The D-band is relationship between sp^3 electronic arrangements with carbon atom vibrations, whereas G and 2D peaks were used to calculate the total amount of graphene layers [14-15]. The full width at half maximum (FWHM) of the 2D peak grows with the increase in the graphene layer, as this pencil-core has a multi-layer structure based on a broad 2D spectrum.

The intensity ratio of the D and the G bands of the pencil-core tape is about 0.42 and 0.57 for area A and B, respectively. These intensities are important to determine the graphene layer. If the intensity is below than 0.5, it considered as low and single-layer graphene, meanwhile higher than 1 is normally multi-layer graphene [16-17]. Thus, this indicates the defect levels in the pencil-core samples for two different area is almost similar. However, the amount of the structural defects for both areas is not large since the D peak is not very broad.

3. Experiment Laser Arrangement

Fig. 3 is the laser arrangement of the proposed Q-switched Zr-Y-Al-Er-doped fibre laser, with the pencil-core engaged as the SA. A short 1-meter length of Zr-Y-Al-Er-doped fibre as an active medium was forward pumped to the 980/1550 nm wavelength division multiplexer (WDM). Then, it went through a polarization controller (PC) to customize the polarization state of light before producing its output via 90/10 output coupler. 10% was tapped as output, and 90% returned to the laser arrangement. The fabricated pencil-core SA was put in the middle of two fibre connectors to allow the generation of pulsed fibre laser with an insertion loss is measured about 0.75 dB. The modulation deepness of the SA is approximately 12.5%. To analysis the optical spectrum, an optical spectrum analyser (OSA, Yokogawa, AQ6375) was used with 0.05 nm resolution, while a 500 MHz oscilloscope (OSC, LeCroy, WaveJet 352A) in tandem with an InGaAs photodetector (EOT, ET-5010F) were used to detect the pulsed train of Q-switched operation. The rise time for oscilloscope is 750 ps, whereas that of the photodetector is less than 50 ps. The total laser arrangement length of the experimental setup is calculated at about 13 meters.

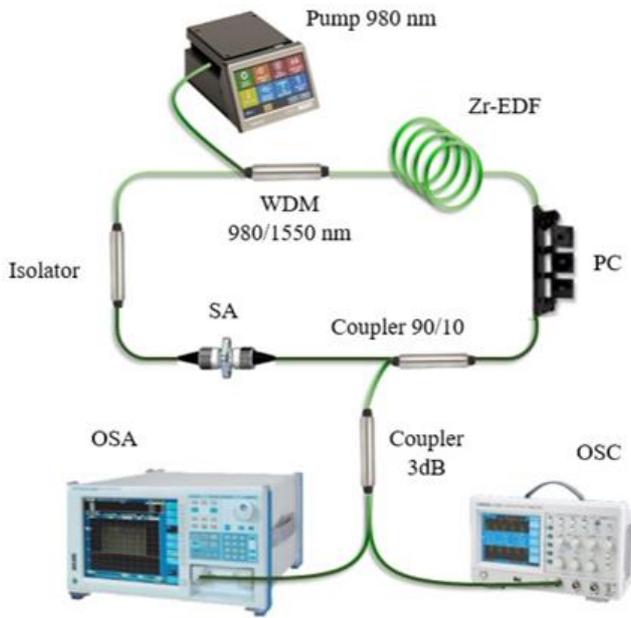


Fig. 3. Experiment arrangement of the Q-switched Zr-Y-Al-Er-doped fibre laser

4. Result and discussion

The proposed pulsed laser of Zr-Y-Al-Er-doped fibre has a lasing threshold without SA at 65 mW, and a Q-switching threshold with SA at 92.4 mW, as illustrated in Fig. 4. The peak lasing is powered by -31.19 dBm at 1566.4 nm, with -26.58 dBm at 1561.2 nm without and with SA, respectively. The spectrum with SA is expected to shift to the shorter wavelength compared to without SA, as the absorbed light decreases with increasing pump power. Moreover, the spectrum also spread a wide transmission from 1530 nm to 1635 nm for both spectrums due to the active medium of zirconia fibre and the SA itself in generating population inversion inside the laser arrangement. As the pump power increases, the repetition rate intensifies as well, while the pulse duration decreases as expected for a normal fundamental Q-switching pulsed laser [17]. The pump power increased until the maximum value of 121.5 mW, as further increases would cause the Q-switching pulsed laser to begin to distort due to instability and the limitations of the operation.

Fig. 5 shows the stable pulse train of the Q-switching pulsed laser, which is gained from the digital oscilloscope when the pump power is fixed at 107 mW. The FWHM or pulse width of 9.9 μ s for an enlarged single envelop of the pulse train. The output power and the repetition rate for this train are 0.89 mW and 16.7 kHz, and thus the pulse energy is calculated to be approximately 53.3 nJ. This pulse train is developed from optical gain switching based on the reaction of the graphene ions' interaction with the oscillating Zr-Y-Al-Er-doped fibre laser.

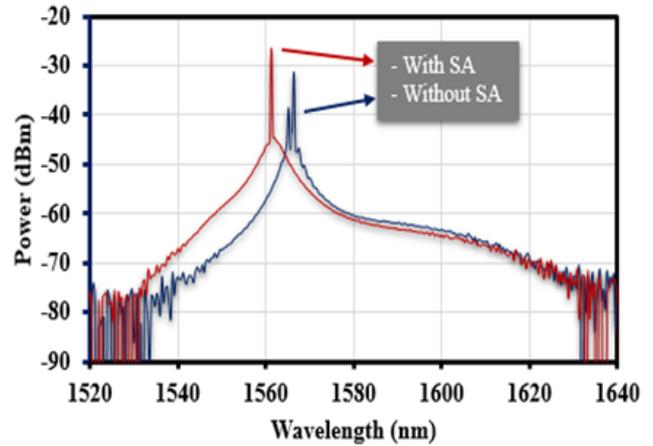


Fig. 4. Optical spectrum of the proposed graphene pencil-core fibre laser (color online)

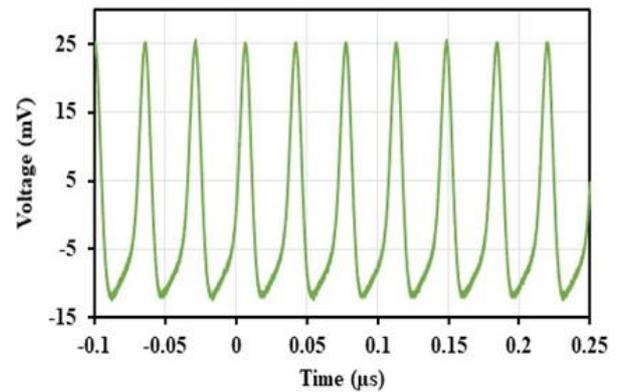


Fig. 5. Pulse laser from oscilloscope trace at pump power of 107 mW with a repetition rate of 16.7 kHz

The repetition rate increased with input pump power from 13.1 kHz until 20 kHz, as shown in the inline chart in Fig. 6. Meanwhile the pulse duration decreased from 0.091 μ s to 0.011 μ s as pump power increased from 92 mW to 121.5 mW. The output power for each increasing input pump power is measured using a power meter at the end of 10% from the 90/10 coupler, achieving the pulsed energy illustrated in Fig. 7. The output power varies from 0.43 mW to 1.53 mW, as the pulse energy achieved ranged from approximately 32.8 nJ to the maximum of 78.1 nJ. Finally, the Q-switching stability is measured by using an RF spectrum analyzer and the spectrum is shown in Fig. 8. The signal-to-noise ratio (SNR) value is 56 dBm, which translates to a strong stability of the Q-switching operation.

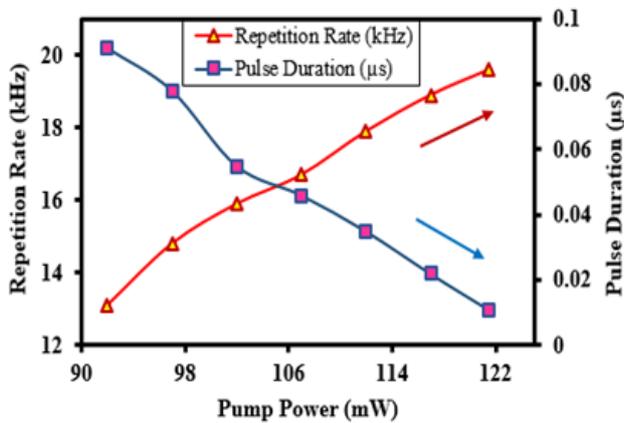


Fig. 6. Repetition rate and the pulse duration as a function of the input pump power (color online)

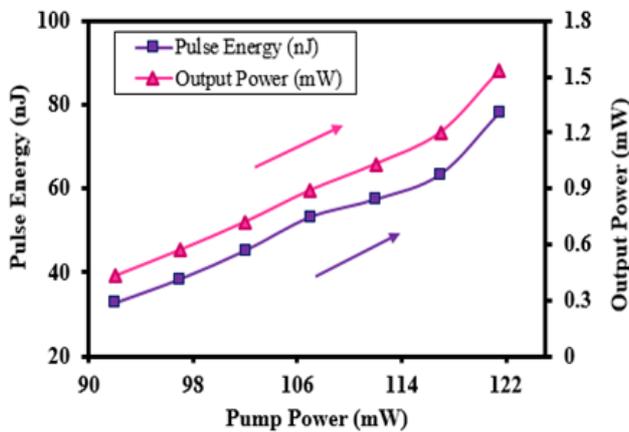


Fig. 7. Pulse energy and output power against input pump power (color online)

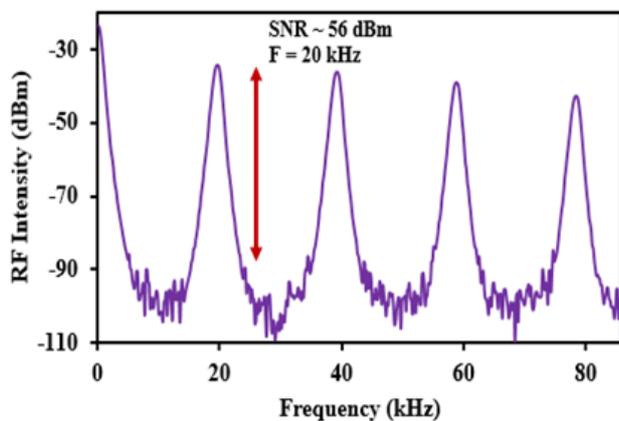


Fig. 8. RF spectrum with repetition rate of 20 kHz

In the previous paper with the same gain medium of Zr-Y-Al-Er-doped fibre, but with different SA of TDF, a significant improvement is achieved using a low-cost and natural resource of graphene pencil-core with improvement in pulse width and maximum pulse energy [18]. The reason is the graphene pencil-core absorb as low

as 2.3% light incident while transferring about 97.7% in the experimental arrangement with minimum loss, enables a strong saturable absorber to create pulsed fibre laser with high pulsed energy. Meanwhile the previous experiment using the same pencil-core as SA but a different gain medium of TDF shows a comparable performance in repetition rate and pulse width [12]. However, they suffer from a higher threshold of input pump power and low pulsed energy. Therefore, the use of Zr-Y-Al-Er-doped fibre and pencil-core as SA, able to generate a significant improvement in pulsed energy, sufficiently thin pulse width and low threshold pump power. Moreover, the short cavity of experimental arrangement, with only 1 meter of Zr-Y-Al-Er-doped fibre, makes it a compact device which is cost effective and has a robust design for use in medicine, biomedical, dentistry and many industrial applications.

5. Conclusion

A flexible and controllable Q-switched pulsed fibre laser using Zr-Y-Al-Er-doped fibre as the gain medium to create major population inversion inside the arrangement was demonstrated. A cost efficient, quickly prepared and readily available material by exfoliating graphene from pencil-core flakes into tape adhesive surface was used as the SA to trigger Q-factor of Q-switched pulsed laser. The maximum repetition rate, pulse width, output power and pulsed energy were 20 kHz, 0.8 μs, 1.53 mW and 78.1 nJ, respectively. These outputs were obtained at a maximum pump power of 121 mW. Thus, a stable, controllable repetition rate, large pulse width and high pulsed energy of Q-switched pulsed fibre laser is important to some applications such as biomedical laser surgery, medical devices and treatment.

Acknowledgements

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References

- [1] E. F. Bernstein, K. T. Schomacker, L. D. Basilavecchio, J. M. Plugis, J. D. Bhawalkar, *Laser Surg. Med.* **47**(7), 542 (2015).
- [2] G. Luca, E. Ceretti, C. Giardini, *Int. J. Adv. Manuf. Tech.* **82**(5-8), 901 (2016).
- [3] P. Todor, E. Pecheva, A. D. Walmsley, S. Dimov, *Mater. Sci. Eng. C* **90**, 433 (2018).
- [4] E. Von Hodenberg, C. Zerweck, M. Knittel, T. Zeller, *Phlebology* **30**(2), 86 (2015).
- [5] A. R. Muhammad, H. Haris, H. Arof, S. J. Tan, *J. Mod. Opt.* **65**(8), 946 (2018).

- [6] M. T. Ahmad, A. R. Muhammad, R. Zakaria, *Laser Phys.* **27**(11) 115101 (2017).
- [7] H. Haris, H. Arof, S. W. Harun, R. Apsari, *Nonlinear Optics, Quantum Optics: Concepts in Modern Optics* **49**(267-275), 3/4 (2018).
- [8] N. A. M. Taib, N. Bidin, H. Haris, N. N. Adnan, *Opt. Laser Technol.* **79**, 193 (2016).
- [9] H. Ahmad, M. Z. Samion, A. S. Sharbirin, S. F. Norizan, *Laser Phys.* **28**(5), 055105 (2018).
- [10] H. Ahmad, M. A. M. Salim, M. F. Ismail, S. W. Harun, *Laser Phys.* **26**(11), 115107 (2016).
- [11] G. Thanasis, R. Jalil, B. D. Belle, L. Britnell, R. V. Gorbachev, S. V. Morozov et al., *Nat. Nanotechnol.* **8**(2), 100 (2013).
- [12] A. A. Latiff, H. Shamsudin, H. Ahmad, *J. Mod. Opt.* **63**(8), 783 (2016).
- [13] A. A. Almukhtar, A. A. Al-Azzawi, S. Das, A. Dhar, M. C. Paul, Z. Jusoh, S. W. Harun, *J. Non-Cryst. Solids* **10**(3), 65 (2018).
- [14] R. Stephanie, C. Thomsen, *Philos. Trans. Royal Soc. A* **362**(1824), 2271 (2004).
- [15] A. C. Ferrari, *Solid State Commun.* **143**(1-2), 47 (2007).
- [16] D. Graf, F. Molitor, K. Ensslin, C. Stampfer, A. Jungen, C. Hierold et al., *Nano Letters* **7**, 238 (2007).
- [17] A. H. H. Al-Masoodi, M. H. M. Ahmed, A. A. Latiff, S. W. Harun, *Chin. Phys. Lett.* **33**(5), 054206 (2016).
- [18] A. M. Markom, N. S. Rosli, A. Hamzah, *Optoelectron. Adv. Mat.* **9**(3-4), 329 (2015).

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