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Passively Q-switched Erbium-Doped Fibre Laser Based on Graphene-Chitin Saturable Absorber

Nur Nadhirah Mohamad Rashid[1], Muhammad Quisar Lokman[1], Siti Nur Fatin Zuikafly[1], Nur Azmah Nordin[1], Hafizal Yahaya[1], Mohammad Faizal Ismail[2], Harith Ahmad[2], Wan Mohd Fazli Wan Nawawi[3], Fauzan Ahmad[1,*]

[1] Malaysia-Japan International Institute of Technology (MJIIT), Universiti Teknologi Malaysia, Jalan Sultan Yahya Petra, 54100 Kuala Lumpur, Malaysia
[2] Photonics Research Centre, University of Malaya, 50603 Kuala Lumpur, Malaysia
[3] Department of Biotechnology Engineering, International Islamic University Malaysia, 50728 Kuala Lumpur, Malaysia

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ABSTRACT

Graphene is a carbon allotrope composed of densely packed sp^2-assembled carbon atoms in a honeycomb-like crystal lattice. It is widely used in various fields of materials science to develop sensors, optoelectronic devices, nanocomposites, and others due to its excellent electronic, mechanical, optical, and thermal properties. Graphene offers several advantages, including ease of fabrication, ultrafast recovery times, low fabrication cost, and low saturation intensities. Its unique zero bandgap property makes it the only material with wavelength-independent absorption, which is advantageous in generating pulsed lasers using saturable absorbers. This study investigates the performance of graphene with a chitin bio-host polymer as a saturable absorber in a 1.5 µm erbium-doped fibre laser. Graphene embedded in chitin was fabricated and utilized in a pulsed laser cavity operating in the wavelength region of 1.5 µm to enable Q-switched pulsed laser operation. The study achieved a pulse energy of approximately 19.83 nJ and a peak power of 10.72 mW. Increasing the pump power from 30.67 mW to 174.28 mW resulted in the highest repetition rate of 63.40 kHz, corresponding to the shortest pulse width of 1.74 µs. These findings have significant implications for applications requiring ultrafast precision and accuracy, such as medical laser equipment and flexible sensors.

1. Introduction

Fibre laser is an established technology that has evolved into a vital tool for various applications such as in medical, biological sensors and industrial practices [1-4]. These light sources are superior to bulk lasers in several aspects, including higher beam quality, cost-effectiveness, flexibility, dependability, and compactness, providing end-users with alignment-free, turn-key operation. Fibre

* *Corresponding author.*
E-mail address: fauzan.kl@utm.my

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lasers produce pulses with enhanced instantaneous power which is crucial for controlling optical processes and enabling time-resolved and high-resolution applications [5].

Among the available approaches for short and stable pulse generation, passive Q-switching and mode-locking methods are the most favoured due to their lack of need for complex and costly active electrical modulators [6-8]. A saturable absorber (SA) is employed in Q-switching and mode-locking technologies; it transforms a continuous wave into pulses by exhibiting nonlinear reduced absorption with increasing light intensity. An ideal SA should have the following features: a broad wavelength range, a fast response time, a high damage threshold, and a low optical loss [9,10]. Categorized into real and artificial SAs, nonlinear amplification loop mirrors (NALMs), nonlinear optical loop mirrors (NOLMs) and nonlinear polarisation evolution (NPE) belong to the latter, relying on the nonlinear effect or birefringence to generate intensity-dependent nonlinear absorption. Real SA, on the other hand, including semiconductor saturable absorber mirrors (SESAM) and low-dimensional nanomaterials, display light intensity-dependent nonlinear absorption [11].

SESAM has become one of the most widely utilized SAs in solid-state and fibre lasers due to their outstanding characteristics which includes low saturation intensity and high modulation depth. However, its production involves complex and expensive fabrication processes, operating with slow recovery times and within narrow saturable absorption bands [8,12,13]. These limits have compelled the laser community to look for alternative SA materials, ultimately leading to a significant field of ultrafast laser technologies based on nanomaterials [14-15] as SAs, such as quantum dots, carbon nanotubes (CNTs) and graphene [5].

Since the discovery of graphene in 2004 [16], 2D atomically thin layered materials have piqued the interest of researchers, who are motivated by the possibility of fabricating novel nanoelectronics, photonics, and optoelectronic devices due to their remarkable and extraordinary properties [17-21]. As SAs, 2D materials are superior in terms of low absorption losses and wide operating wavelength range [22]. Besides, 2D materials have fast saturation recovery and high damage threshold, making them suitable for generating ultrafast pulses with high energy [23].

Graphene, a carbon allotrope with an sp^2 hybridised hexagonal lattice, is the pioneer of all subsequent 2D materials [24,25]. Graphene has the potential to be utilised extensively as SA for all kinds of fibre lasers due to its remarkable optical features, such as its ultrabroad tuning range, low saturable absorption threshold, and high modulation depth, offering new possibilities for developing ultrafast mode-locked fibre lasers [23,26]. In 2009, Bao *et al.,* [27] first demonstrated the usage of graphene as the SA for the mode-locking of an erbium-doped fibre laser (EDFL).

Several methods for fabricating SA devices out of graphene has been reported including chemical exfoliation, chemical vapour deposition (CVD), liquid-phase exfoliation (LPE), and electrochemical techniques among many others [11]. The synthesis of graphene plays an important role in producing high performance graphene-based SA. However, higher quality graphene is usually produced through more complicated and expensive technique such as CVD.

In the preparation of film based SAs, a host polymer is used to bind the material together and for easier handling during pulsed laser generation. In this study, chitin is used instead of synthetic polymer to produce a graphene-based polymer composite. Chitin, the second most widespread natural polymer after cellulose, is found in the exoskeletons and cell walls of crustaceans, insects, and fungi [28]. It has been employed in numerous applications, including in biomedical, nanotechnology, electrical, and solar cell sectors, owing to its distinctive biochemical features, including biodegradability, biocompatibility, non-toxicity, and ability to form films [29,30]. In addition, chitin's resistance to high acidity and harsh conditions makes it excellent for the fabrication of films in high-temperature and high-power laser operations. This is a problem existing SA is facing because their performance is limited by the low heat resistance of their host polymers. Although it

depends on factors such as the degree of deacetylation, molecular weight, and processing conditions, chitosan, the linear polysaccharide counterpart, is known to have lower heat resistance than chitin [31]. This advantage encourages using chitin as a host polymer in producing SA for pulsed laser generation. A mode-locked pulsed fibre laser in the 2.0 µm range was reported by Zuikafly *et al.,* [32] by using graphene embedded in chitin as SA which generated an 11.35 MHz repetition rate and 7.03 ps pulse width. Therefore, the performance of the graphene with chitin as a host polymer as the SA in the 1.5 µm EDFL will be discussed in this paper.

2. Methodology

2.1 Preparation of Graphene

This work will use a conductive graphene-PLA-based 3D printer filament purchased from blackmagic3d. The filament is 1.75 mm in diameter and has a volume resistivity of 1 ohm-cm. It was extruded through a 3D printer nozzle of 0.7 mm in diameter at 210 °C to reduce its diameter to 700 µm, allowing for an easier mixing process. The filament was then mixed with 1 ml of tetrahydrofuran (THF), which helped dissolve the PLA, and placed in ultrasonic bath for 10 minutes to create a graphene-THF suspension. Zuikafly *et al.,* [30] previously demonstrated that 25 mg of extruded graphene filament dissolves best in 1 ml of THF after vigorous shaking.

The host polymer, chitin, was extracted from oyster mushrooms (Pleurotus Ostreatus) in the following process [29,31]. The mushrooms were blended for 5 minutes and then subjected to 30 minutes of hot water extraction at 85 °C. The mushroom tissue was treated with alkali (1 M NaOH) for 3 hours at 65 °C. The extracted tissues were diluted to a concentration of 0.8 %w/v and stored at 4 °C until further use. The chitin was then mixed with the graphene suspension at a 2:3 ratio. The mixture was ultrasonicated for 60 minutes to ensure that the graphene was evenly dispersed in the polymer matrices. 5 mL of the mixture was then transferred to a petri dish (32 mm diameter, 10 mm height) and left to dry for 36 hours at room temperature, producing a graphene-chitin SA film. The procedure can be referred to Zuikafly *et al.,* [29].

2.2 Experimental Configuration for 1.5 µm Wavelength Fibre Laser Generation

The experimental configuration for the Q-switched EDFL performed in this study is shown in Figure 1. A 3 m erbium-doped fibre (EDF) was utilised as the gain medium to operate in the 1.5 µm region. The laser cavity was pumped with 900 mW of power from a 980 nm laser diode via a 980/1550 wavelength division multiplexer (WDM). The ring cavity's unidirectional light propagation was maintained via an optical isolator. Q-switched pulses were generated by incorporating a graphene-chitin SA between two FC/PC fibre ferrules in the cavity. The laser output was extracted from the cavity through a 90:10 coupler, which maintains 90 % of the light in the ring cavity to continuously oscillate. The output characteristics were monitored using an oscilloscope for time domain measurement and an optical spectrum analyser (OSA) for measurement in the optical domain. A radio frequency spectrum analyser (RFSA) was also utilised to measure the outputs in the frequency domain.

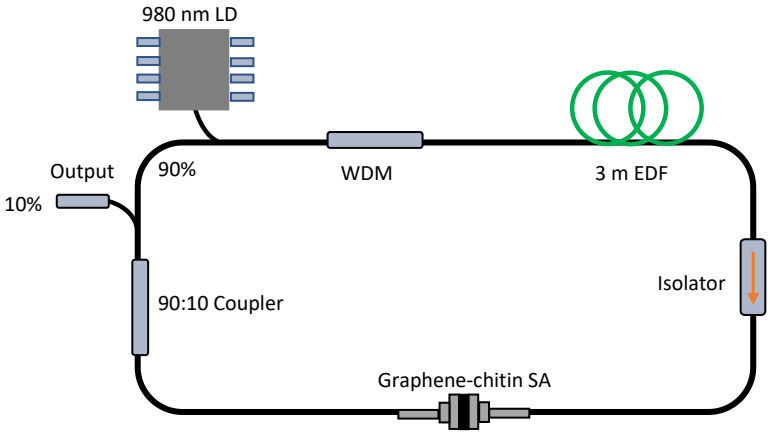

Fig. 1. Experimental configuration of the proposed Q-switched EDFL

3. Results and Discussions

Figure 2 displays the optical spectrum of the Q-switched EDFL using the fabricated graphene-chitin film as SA at a maximum input pump power of 174.28 mW. An operating wavelength of approximately 1559 nm was recorded with a 3-dB bandwidth of around 1.2 nm. Stable Q-switched performance was gained once the pump power was increased above the threshold of 30.67 mW and remained stable as the pump power was steadily increased up to the maximum pump power of 174.28 mW. The SA in this study had a lower threshold pump power than the single-walled carbon nanotube saturable absorber (SWCNT) reported by Ahmed *et al.,* [32], which reported the threshold value at 48.5 mW. This was due to graphene's lower saturation intensity [33,34].

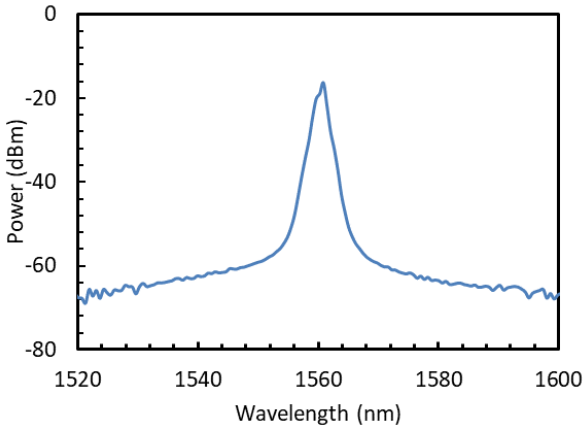

Fig. 2. Optical spectrum of Q-switched EDFL based on graphene-chitin SA at maximum input pump power

Figure 3(a) shows the pulse repetition rate of 63.40 kHz with a pulse-to-pulse separation of 15.8 µs. The pulse's full width at half maximum (FWHM) was 1.74 µs, as observed in Figure 3(b). Each Q-switched pulse envelope had an asymmetric intensity profile with no amplitude modulation demonstrating that the self-mode locking phenomenon had been effectively controlled.

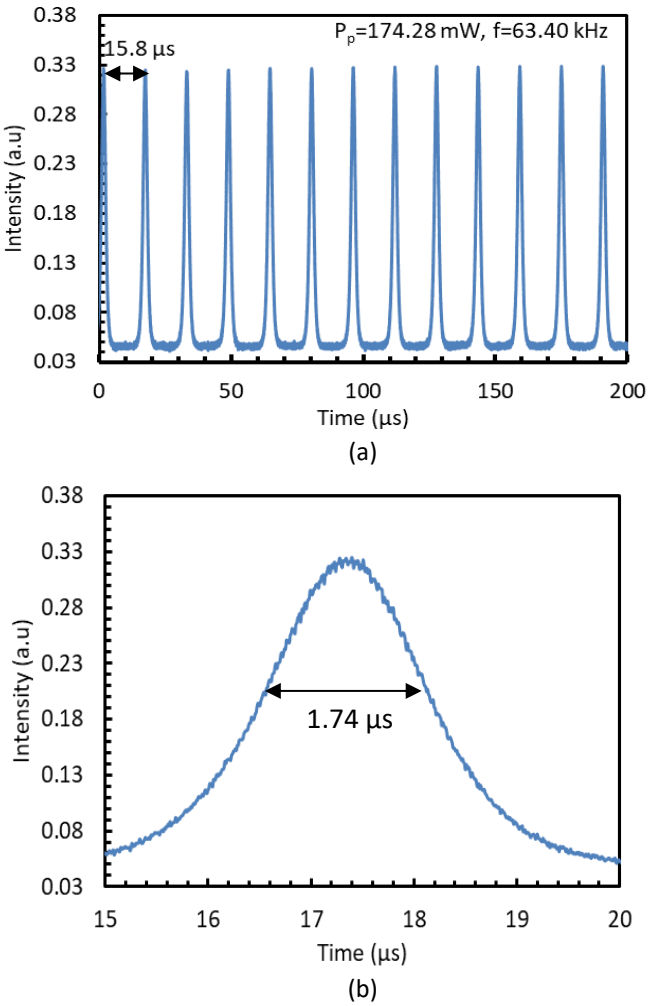

Fig. 3. Oscilloscope trace of (a) the pulse train at the pump power of 174.28 mW with pulse-to-pulse separation of 15.8 µs, and (b) the single-pulse envelope of the shortest pulse width of 1.74 µs

The relationship between the repetition rate, pulse width and pump power is illustrated in Figure 4. In contrast to a mode-locked fibre laser, in which the repetition rate depends on the cavity length, the Q-switched pulse repetition rate varied with the input pump power [33,35]. With increasing pump power, the repetition rate increased from 22.65 kHz to 63.40 kHz. When the pump power was increased from 30.67 mW to 174.28 mW, the pulse width dropped from 7.29 µs to 1.74 µs. As more power was pumped into the cavity, the gain population was excited to a saturation state more rapidly. This enabled a shorter pulse width at a faster pulse repetition rate. The pulse repetition rate and pulse width patterns are consistent with the passive Q-switching theory [36].

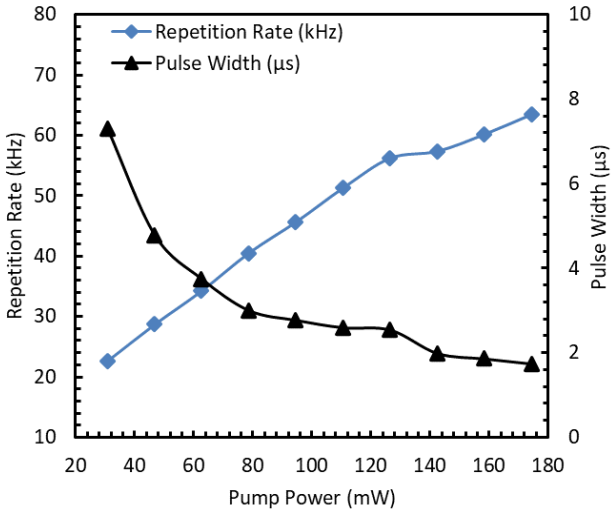

Fig. 4. Pulse width and repetition rate as a function of pump power

The peak power and pulse energy of the Q-switched EDFL using graphene embedded in chitin polymer as a function of pump power is shown in Figure 5. When the pump power was increased from 30.67 mW to 174.28 mW, the pulse energy was observed to increase from 11.36 nJ to 19.83 nJ. The peak power also showed a similar pattern to that of pulse energy, where the peak power increased from 1.46 mW to 10.72 mW. Figure 6 shows the Q-switching radio frequency spectra. As can be observed, the SNR at the pump power of 174.28 mW was 57.19 dB. This SNR value showed that the Q-switched pulsed laser operated at good stability, indicating the graphene-chitin based SA's high quality and thermal stability.

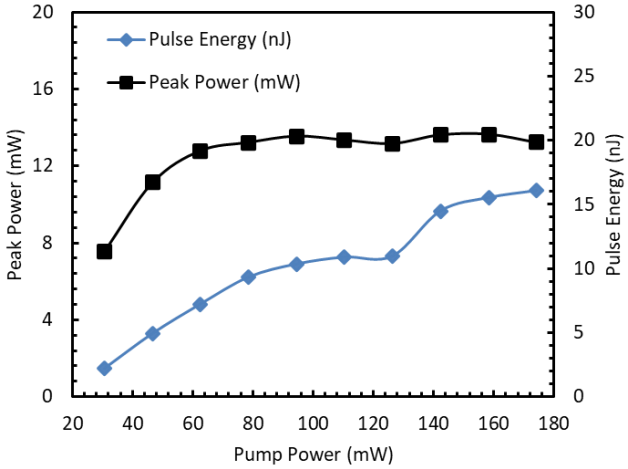

Fig. 5. Pulse peak power and pulse energy as a function of pump power

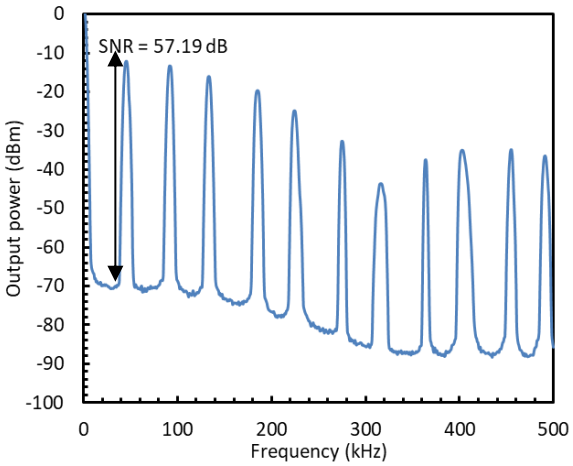

Fig. 6. RFSA measurement signal to noise ratio at a pump power of 174.28 mW

4. Conclusions

The aim of this study was to fabricate graphene using the cost-efficient LPE method with chitin as the host polymer. The synthesized graphene, embedded with chitin, was then employed in a pulsed laser cavity operating at a wavelength of 1.5 µm to enable Q-switched pulsed laser operation. The experimental results yielded impressive findings. The maximum instantaneous peak power and pulse energy achieved were 10.72 mW and 19.83 nJ, respectively. By increasing the pump power from 30.67 mW to 174.28 mW, the laser generated a maximum repetition rate of 63.40 kHz, along with the shortest pulse width measured at 1.74 µs. These results demonstrate the successful integration of graphene with chitin as a SA in a pulsed laser system. The combination of these materials opens up promising opportunities for the development of highperformance lasers with precise control over pulse characteristics. The obtained peak power, pulse energy, repetition rate, and pulse width highlight the potential of this graphene-chitin composite in applications that demand ultrafast precision and accuracy. This includes areas such as medical laser equipment and flexible sensors, where the ability to generate Q-switched pulsed lasers with desirable properties is of utmost importance.

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