Q-switched in figure of 8 by using graphite flakes as saturable absorber

Mofaq Alsaady*¹, NA Awang¹ and Thoalfiqar A Zaker²

¹Faculty of applied science & Technology (FAST), department of physics, Universiti Tun Hussein Onn Malaysia, Pagoh, Johor, Malaysia.
²Faculty of Science, department of physics Al-hamdaniya University, Iraq

haidermofaq51@gmail.com

Abstract. In this study, a successful experiment has been reported on pulse compression in the Q-switched fiber laser by utilizing graphite flakes as a saturable absorber (SA). The sputter deposition method was used to deposited graphite flakes as SA, incorporated into the bore of the laser in order to compress the width of the pulse in the operation of Q-switching. The small repetition rate at 29.6 kHz was mentioned as the maximum power of the pump with the single-to-noise ratio (SNR) ~30dB was required to compress the pulse. Accordingly, graphite flakes have the ability to be utilized as an effective SA in producing pulse compression and Q-switching mode, that will be may fixedly lead to further enhancement in the fiber laser pulsed.

Keywords: Q-switching fiber laser, graphite flakes, saturable absorber.

1. Introduction

The short pulse laser has been widely used in many fields as medicine, remote sensing, laser treatment, and telecommunications [1,2]. The two common using methods: Mode locking [3], and Q-switching [4]. However, using these methods, the energy of pulse limited to the Nano-Joule level, and the rate of repetition pulse is fixed in many applications given its operating mechanism such as laser machining and marking, the OTDR (optical time domain reflectometry) and laser ranging [5,6], spectroscopy, biomedical diagnoses, fiber communication [7], environmental sensing, microwave optics, metrology and range finding [8]. Ultrafast pulses are normally Q-switched or mode-locked and are enabled by applying active modulation techniques [9] and other methods in order to get short pulses. The Q-switched fiber lasers can be classified depending on the Q-factor type which divided into two types passive and active Q-switched. The passive Q-switched fiber lasers have regained more attention compared to others due to low cost, simple configurations, and their compactness. The Q-switched fiber lasers actively fiber lasers are requiring many additional switching electronics compared with the passive [10,11,12].

On the other hand, SA is considered one of the important items for passively Q-switched fiber laser, and SA is also very important to the output of Q-switching execution which has attracted immense interest and attention of many researchers. In order to achieve a Q-switched fiber laser and passively
mode-locking, a SA is required in the laser cavity. Although, the time response of the SA does not necessary to be shorter than the bore round-trip time, but it needs to be shorter when it compared to the time of the iron life in the upper levels of the media given the time of the duration pulse is measured by the time of the gain depletion following the saturation [13]. In addition, the ideal saturable absorber for the operation of Q-switching wants to have high damage threshold, good thermal stability, and large modulation depth, to maintain the operation of the stable pulse with high pulse energy [5]. The SESAM (semiconductor saturable absorber mirror) is one of the most commonly SA which is used for the Q-switched fiber laser passively despite it has various negatives such as small response bandwidth and having a low damage threshold, which makes it very limits to use in the applications of passively Q-switched fiber lasers [11,14]. SESAM is a well-determined method to produce pulses with the fast ultra in Er-doped (Erbium-doped) fiber lasers [1], however, the operation of the SESAMs fabrication is an expensive and complex process.

Graphene has attracted the attention of researchers recently as a new material used in the Q-switching pulse lasers as a saturable absorber [16,11]. In the theoretical side, Graphene is a highly absorbable spectrum and Q-Switch from visible to distant infrared spectroscopy, which differs from classic SA Cr2+: ZnSe, SESAM, etc., [17], graphene has a rapid recovery factor of up to ~200 fs compared with other materials that gave less than this amount [8]. In addition, requiring simple fabrication and large response bandwidth [17,18,21,22]. Moreover, graphene has a wavelength independent SA, due to its band gap property zero unique [15] allowing nanoparticle graphene SA to be formed, with its inclusion deepness enhanced between 11% and 20% [5].

Since the discovery of graphene, there have been many studies done using graphene SA in the passively Q-switched fiber lasers [1,11,23-29] which are implausibly systems in this field. Graphene has been provided thermal conductivity and a large response bandwidth compared with the SESAM, these properties are making graphene useful to the produce [11]. Many studies have been demonstrated to support this fact using graphene SA in the tunable Q-switched fiber lasers [2,10-12,30]. In 2011, a Q-switched fiber laser has been developed using a tunable filter and graphene-film SA which wrapped a tunable wavelength range of 32 nm [11]. After two years 2013, Armed et al, have been reported that a graphene Q-switched fiber laser tunable based on Bragg grating fiber tunable, of 10 nm [2], which leads to an increase the complicated the system of the laser. The graphene-film SA which is used in the notified Q-switched fiber laser tunable compared to the graphene SAs based on sharpened fibers give’s more benefits such as simplicity to modularize and large interaction length, having a high damage threshold and package [31]. Furthermore, due to the intervention multimode, sharpened fibers can be provided in addition to that can use as tunable refineries in tunable fiber lasers and wavelength-dependent transmissions [32,33]. Therefore, it is expected that peaked fiber coated with graphene use as both SA and a setting item in the tunable Q-switched fiber laser passively, thus leading to production the costly and complicated.

In this study, we report the use of graphite flakes as both a SA and a tunable filter. The graphite SA is collected of a fiber which has been plated with graphite which is a good show for a graphite flakes-based Q-switched fiber laser without the need for any additional setting item.

2. Preparation of the Graphite Flakes
In preparing the graphite flakes, a mechanical exfoliation approach was adopted to fabricate the graphite flake samples (see Figure 1(a)), which is similar to the approach used in preparing Black Phosphorus-based SA for applications of ultra-short pulse laser [34]. The technique we used has advantageous to give its reliability and simplicity, and where the whole process of fabrication is set free from difficult chemical procedures and the use of expensive instruments. First, relatively thin flakes were peeled off from pieces of commercially obtained graphite flakes in which small pieces were placed onto adhesive tape (Figure 1(b)) attached between the end surfaces of two fiber ferrules (Figure 1(c)). This procedure took about 2 minutes to complete as graphite flake material can be easily damaged and must be handled
carefully. Next, the graphite flakes-SA was inserted into the laser cavity by applying it between two fiber ferrules with a fiber connector as the display in Figure 1(d).

![Figure 1](image1.png)

**Figure 1.** (a) Graphite flakes. (b) Crushed graphite flakes. (c) Graphite flakes deposited on fiber ferrule. (d) Sandwiching the crushed graphite flakes between two ferrules by using a mating sleeve.

### 3. Experimental Setup

As displayed in Figure 2, a passively Q-switched fiber laser using the graphite flakes as SA was structured using an Oclaro LC 96A74P-20R laser diode with a 980 nm peak wavelength of pump. The laser diode was joint to the laser cavity via a 980/1550 wavelength division multiplexer (WDM). The 2 m length of erbium-doped fiber (EDF, Fibercore) as the gain medium, with a 5.09 dB/m absorption coefficient of a 979 nm wavelength, 5.8 μm mode field diameter (MFD) with a 0.23 numerical aperture (NA), was then connected to the 1550 arm of the WDM. The EDF was next spliced with a 2*2 optical coupler (optical ratio=50:50, operating wavelength and bandwidth=1550±20) where the output of the coupler was applied to an independent polarisation isolator (ISO) to ensure unidirectional operation when the other one going back to the WDM. A polarisation controller (PC) used after the isolator to
control the cavity polarisation. Then to 2 x 1 optical coupler (optical ratio=90:10, operating wavelength and bandwidth=1550±20) was used in the second ring. 90 was back to the 50/50 OC and The fiber (10%) of the OC (optical ratio=10:90, operating wavelength and bandwidth=1550±20), then connected to a 50/50 OC to an optical spectrum analyzer (OSA) and oscilloscope. The laser cavity length is around 11 m. The laser execution was simultaneously detected using (Tektronix MDO 4104) a digital oscilloscope with (PD, Thorlabs DET08CFC/M) 5 GHz photodetector, and (OSA Yokogawa AQ6370D) optical spectrum analyzer. While graphite flakes were used as a saturable absorber in the cavity, minimal graphite grinding occurred on the tape which was applied between the two ferrule fibers.

**Figure 2.** Experimental setup of the passively Q-switched fiber laser using the graphite flakes as SA.

4. **Results and Discussion**

Figure 3 displays the laser pulse train have taken from the oscilloscope via a 5 GHz bandwidth of the photodetector we used at the \( P_p \) of 16.6 mW. The pump power \( P_p \) at 70 mA (16.6 mW), a stable Q-switched pulse was achieved as can be seen in Figure 3(a). With increasing \( P_p \), the laser continues to appear the Q-switched shape, with an increased repetition rate and the \( P_p \). The last pulse appeared at 370 mA (194.5 mW) of the pump power (Figure 3(b)) after that the Q-switched pulse disappeared. However, when the \( P_p \) reaches 194.5 mW, the Q-switched pulse train has lost and could not be fixed even with arranging full modification of the PC. For the minimum and maximum finding of the Q-switch, Figure .4. showing a pump power at 16.6 mW the output spectrum listed by the OSA when the cavity was embedded with the graphite flakes.
The laser spectrum was also observed having a broad laser bandwidth at the first reading Q-switched signal, as shown in Figure 4. above, which covered the wavelength range between 1547 nm to 1560 nm. One of the factors that contributed to the broadening of the laser bandwidth was due to the large normal dispersion of the fiber cavity. It is also supposed that this graphene flakes-SA could be applied to other wavelengths as well. Also, with a small repetition rate, pulse compression can be done which happened when gaining energy from the pump laser. This is because of those non-thermal electrons de-excite via e-e collisions to a thermal bath which deposits its energy into the surrounding lattice or atoms via electron-phonon collisions [35].

In this situation, the free electrons are accelerated in the laser field, where the electron density is finally rising sufficiently to cause pulse compression in the laser cavity to occur [36][37]. Therefore, this demonstrates that graphite flakes have the ability to compress the pulse, which is similar to the metal
pulse compressor in the bulk laser system [38]. Figure 5 illustrates a linear increment of the repetition rate from 0 kHz to 29.6 kHz as the increment of the \(P_p\) from 16.6 mW to 200.4 mW. Whereas, linear decreasing of the pulse width from 0 μs to 6 μs, displaying the normal characteristics of the Q-switching operation [39].

![Figure 5. Repetition rate and pulse width against pump power.](image)

Figure 5. Repetition rate and pulse width against pump power.

Figure 6 shows the radio frequency (RF) spectrum for generating pulse obtained at 29.7 kHz resolution bandwidth (RBW) and observed having a strong signal peak with a 29.6 kHz repetition rate, and 30 dB signal-to-noise ratio (SNR). Also, with a single repetition rate appearing in the RF spectrum, this suggests that the waveform in the oscilloscope is a cosine wave pattern that corresponds to the broad pulse width.

![Figure 6. Radio frequency spectrum at 194.5 mW of pump power.](image)

Figure 6. Radio frequency spectrum at 194.5 mW of pump power.
5. Conclusion
The passive Q-switching of an EDFs using graphite flakes as a SA was investigated in this study where this SA generated pulse repetition rates between 0 kHz and 29.6 kHz at the maximum pump power of laser system, with SNR 30 dB. It was shown that a small repetition rate was required to compress the pulse, which has been done by the deployment of graphene SA in the laser cavity. Accordingly, this finding may lead to further research to be undertaken in the photonics field on the capability of the graphene flakes-SA in compression of pulses.

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