Tunable passively Q-switched fiber laser of graphite flakes saturable absorber

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Abstract This study demonstrated the performance of a passively Q-switched fiber laser by using graphite flakes at different EDF absorption which are EDF 1 and EDF 2 at 5.09 dB/m and 7.28 dB/m, respectively. The system is designed as a single ring cavity by employing a graphite flakes saturable absorber (SA) with 23.82% of saturable absorption. The experimental result shows that a wide-band tunable cover from 1544 nm to 1560 nm and 1552 nm to 1570 nm for EDF 1 and EDF 2 respectively. The EDF 2 is the best gain medium due to the conventional wavelength band at C band and L band region.

Introduction

Passive Q-switched is a technique to produce short pulses with a high peak. This technique is simple in setup, more compact compared to active Q-switched. Generally, a passive technique used saturable absorber to generate a pulse in the microsecond to nanosecond in laser cavities. However, in active Q-switched semiconductor SA also used to generate Q-switched whereby this technique no longer investigated due to limited operating wavelength and high cost in fabrication. In passive Q-switched, SA requires longer recovery time than the cavity round trip time because the pulse duration depends on the time to deplete the gain after the SA saturates [1].

The generation of a pulsed laser is demonstrated via Q-switched fiber laser with saturable absorber (SA) such as graphene [2-4], graphite [5], single wall carbon nanotube (SWNTs) [6] and topological insulator (TIs) [7]. This is due to the advantages of SA which has a broadband operation, easy fabrication and low cost. However, the SWNT is good in term of saturable absorption and ultrafast recovery time but it suffers intrinsic drawback. The intrinsic drawback of SWNT can be prevented if graphene SA is used. On the other hand, the gain media in single ring cavity involve a dopant either erbium, thulium and ytterbium ions in order to generate Q-switched fiber laser. Erbium-doped fiber (EDF) act as a gain medium lies in the C-band region which is important for application in communication. Nevertheless, in order to transmit more data in communication system enhance researcher to investigate other bands of EDF such as S-band [8-10].

An SA has been attracting great interest in graphene, carbon nanotube (CNT) and graphene oxide to produce Q-switched pulse due to the low-cost system. According to Popa et. Al [11], graphene Q-switched fiber laser has been proposed wide band from 1552.5 nm to 1555 nm range with pulse duration of ~2 µs with a repetition rate at 70 kHz meanwhile, CNT SA [12] can tuned wavelength from 1555 nm
to 15560 nm with pulse duration of ~7µs and repetition rate at 12 kHz. In general, the random phase relationship comes up from oscillation of different modes can be determined by SA resulting in the pulse Q-switched in microseconds. Based on previous work, the pulse duration of Q-switched and repetition rate can be considered in microsecond (µ) region and kilohertz (kHz) respectively which is depending on pump power [13].

In this paper, the tunable Q-switched fiber laser based on graphite flakes is demonstrated. The laser cavity of this setup is 18.17 m with two different EDF absorption coefficient which are 5.06 dB/m: EDF 1 and 7.28 dB/m: EDF2 are used. The broadband absorption of graphite flakes can covers range from 1544 nm to 1560 nm and 1552 nm to 1570 nm for EDF 1 and EDF 2, respectively. The modulation depth of graphite flakes is 23.82 % with a saturation intensity of 0.031 MW/cm². The wavelength tunability of graphite Q-switched from shorter wavelength to longer wavelength created decreasing in pulse width but increasing in repetition rate.

**Characterization of Erbium doped fiber**

There are two types of EDF (EDF 1 & EDF 2) with different absorption coefficient used in this work; 5.09 dB/m and 7.28 dB/m. The other parameters of the two EDF can be shown in Table 1. The setup of the characterization of the Erbium-doped fiber amplifier (EDFA) is illustrated in Figure 1. The pump laser is connected to the wavelength division multiplexing (WDM) to produce 1550 nm so that the wavelength lies in the C or L band region, which is suited with EDF absorption characteristics. The output of EDF is connected to the isolator, which is known as an optical component that can ensure one direction operation in the fiber cavity. The presence of isolator can reduce noise peak in the ASE spectrum caused by oscillation reflection [14-15]. Optical spectrum analyzer (OSA) was used to observe the output signal spectrum. The wavelength of EDF depends on the EDF itself which lie at C band region or L band region as refer in Table 2.

| Fiber parameters        | EDF 1  | EDF 2  |
|-------------------------|--------|--------|
| Peak absorption (dB/m)  | 6.43   | 18.93  |
| Absorption coefficient (dB/m) | **5.09** | **7.28** |
| Attenuation (dB/km)   | 2.8    | 8.23   |
| Fiber diameter (µ)     | 124.9  | 125    |
| Numerical Aperture     | 0.23   | 0.25   |
| Operating Wavelength (nm) | 1550  | 1550   |
| Material dispersion    | -91.6  | -91.6  |
| λ2(ps²/km)             | 117.1  | 117.1  |
Table 2: Optical wavelength bands [16]

| Band | Wavelength range |
|------|------------------|
| O    | 1260-1360        |
| E    | 1360-1460        |
| S    | 1460-1530        |
| C    | 1530-1565        |
| L    | 1565-1625        |
| U/XL | 1625-1675        |

Figure 1: Setup of Erbium-doped fiber

Figure 2(a) and (b) show the spectral response of amplified spontaneous emission (ASE) for EDF 1 and EDF 2 by varying the pump power from 11.2 mW to 325.5 mW. The peak power of EDF 1 and EDF 2 are -2.39 dBm and 2.22 dBm respectively at the pump power of 325.5 mW. It is proven that the higher absorption coefficient of EDF gave a higher peak power because of more excitation of erbium ion occurs during the spontaneous emission process. The ASE spectra for EDF 1 lies in the C-band region whereas EDF 2 lies at C and L band regions [17]. This is due to the excitation of the erbium ions which provide amplification of signal in the region without introducing any effects of gain narrowing [18-20].
Figure 2: Spectrum ASE of (a) EDF 1 (b) EDF 2
Preparation and characterization of graphite flakes SA

Graphite flakes were deposited on the surface of fiber ferrules. Before the deposition process fiber ferrules which made up of borosilicate glass was cleaned by isopropyl alcohol. The cleaning technique should be performed in the figure of eight wiping action to avoid contamination on surface fiber ferrules. Then, the surface of fiber ferrules was checked for contamination using fiberscope, FS201 Thorlabs. The graphite flakes were transferred to scotch tape for the exfoliation process as shown in Figure 3. The core and cladding of fiber ferrules is shown in Figure 4 after the exfoliation process.

Figure 3: Exfoliation process of graphite flakes

Figure 4: Zoom in of fiber core and cladding

Graphite flakes are characterized by twin detector method to measure the non-linear saturable absorption such as modulation depth, saturation intensity and non-saturable absorption of graphite flakes as shown in Figure 5. The central wavelength of mode-locked pulse seed operates at 1558nm with a repetition rate of 16.8 MHz. Then, the output port of WDM is connected to 3m EDF. The isolator is
inserted in between 3m EDF and 50:50 coupler to ensure a unidirectional light propagation [21]. A graphite flakes SA is attached in between of 50:50 OC and OPM 2. Another port of OC is coupled to the OPM 1 which is designated as reference signal while OPM 2 as power absorption measurement.

![Setup of the twin detector method](image)

**Figure 5**: Setup of the twin detector method

Figure 6 shows the modulation depth and saturation intensity of the graphite flakes are 23.85 % and 0.031 MW/cm² respectively, which could be obtained from power dependent absorption data. The equation for saturable absorption of graphite flakes can be expressed as

\[
\alpha(I) = \frac{\alpha_s I}{1 + I/I_s} + \alpha_m
\]

The non-linear saturable absorption can be observed from 28.2 % to 52.05 % at saturation. This shows that the optical absorption increases by 23.85 % when graphite flakes saturated at an intensity of 0.014 MW/cm² giving a modulation depth of 23.85 %. In general, a stable operation of Q-switched has a high modulation depth of more than 10% [12,22]. As the higher modulation depth, the larger non-linear saturable absorption is obtained whereby it will increase the insertion loss and reduce the performance of the laser. Thus, the absorption of the saturable absorber (SA) should be incautiously controlled [23-25]. However, a larger modulation depth of SA may indicate better pulse shaping ability and stabilization of the single pulse operation [4,26]. The pump power increase, the more gain signal produces due to the saturation of graphite SA which indicate of passively Q-switched pulses dependent on the saturation level of SA [27].
Figure 6: Modulation depth of graphite flakes

Tunable

Q-switched fiber laser was tuned at several wavelengths in C band region. The tunable bandpass filter (TBF) passively Q-switched configuration as shown in Figure 7 has a 90% output coupler that is connected to the input of the TBF. While the output of TBF is connected to 1550 nm WDM. In the generation of Q-switched fiber laser, TBF is inserted into the cavity as the tuning mechanism.

Passively Q-switched optical fiber laser was tuned using TBF in order to determine the performance range of graphite flake SA. The tuning range of the laser spectrum was measured at a fixed pump power of 118.1 mW after graphite flakes SA was inserted inside the resonator as shown in Figure 8(a) and (b). In overall, the range of wavelength was tuned from 1544 nm to 1570 nm for both EDF. Laser tunability was obtained by adjusting the TBF to the desired wavelength with tune step of 2 nm. The tuned wavelength range covers partially C-band for EDF 1 and C and L band for EDF 2. The average power of EDF 1 and EDF are less than -20 dBm and less than 0 dBm respectively. This was due to the higher concentration of Erbium ions contained in the laser cavity. Thus, the stability of the Q-switched pulse could be attained within the wavelength range of 1544 nm to 1570 nm for both EDF. However, the Q-switched pulse disappeared when the tuned wavelength exceeded the range 1560 nm and 1570 nm for EDF 1 and EDF 2 respectively.
Figure 7: The setup of tunable passively Q-switched fiber laser employing TBF.
The pump power for EDF 1 and EDF 2 are fixed at 118.1 mW which showed the tuning range from 1544 nm and 1570 nm. The pulse duration for EDF 1 and EDF 2 are 119.6 µs and 27.97 µs at 1544 nm and 1552 nm wavelength respectively, as shown in Figure 9(a) and (b). It can be concluded that pulse duration in passively Q-switched fiber laser dependent on the pump power. As the higher the pump power applied, the more gain is needed to saturate the SA which give smaller pulse duration [28]. On the other hand, the pulse width for EDF 1 and EDF 2 are 7.38 µs and 4.17 µs. In theory, when pulse to pulse spacing is equal or longer than the upper state lifetime, most of the obtainable inversion will be lost via spontaneous decays. Therefore, the repetition rate of passively Q-switched fiber laser happens in a few kHz [29-30].

The repetition rate for both EDF 1 and EDF 2 are 8.33 kHz and 35.74 kHz as shown in Figure 10(a) and (b). From the figure below, the signal-to-noise ratio (SNR) of EDF 1 and EDF 2 can be calculated by deduction of the highest peak power to the lowest peak power [31]. The repetition rate increase with pump power as well as the SNR value. In this paper, the highest SNR value is the best compared to the others due to the more signals can be received in order to generate Q-switched pulses.

Figure 11 shows the passively Q-switched fiber laser pulse in terms of pulse repetition rate and pulse width at a wider range of wavelength. The wavelength point for Q-switching is observed at 1544 nm to 1560 nm and 1552 nm to 1570 nm for EDF 1 and EDF 2, where the pump power is fixed at 118.1 mW. The wavelength tuning for both EDF 1 and EDF 2 are obtained due to the result of the limitation of the ASE spectrum of the EDF itself lies in C-band and L-band region [48]. Figure 11(a) and (b) illustrate the relationship between repetition rate and pulse width with wavelength. As the wavelength point increases from 1544 nm to 1560 nm and 1552 nm to 1570 nm for both EDF, the pulse width shows a decreasing line for EDF 1 and increasing line for EDF 2. On the other hand, for repetition rate, the repetition rate increased in EDF 1 but decreased in EDF 2. This is because the trend of the graph of the repetition rate and pulse width are different as shown in the figure below due to the pattern of the ASE spectrum of the EDF itself.
Figure 9: Pulse train of passively Q-switched fiber laser at a pump power of 118.1 mW for (a) EDF 1 (b) EDF
Figure 10: Repetition rate of passively Q-switched fiber laser at a pump power of 118.1 mW for (a) EDF 1 (b) EDF
Figure 11: Pulse width and pulse repetition rate as a function of wavelength for (a) EDF 1 (b) EDF 2

Figure 12: Pulse width and pulse repetition rate as a function of wavelength for (a) EDF 1 (b) EDF 2
Conclusion
The performance of a passively Q-switched fiber laser by using graphite flakes at different EDF absorption which are EDF 1 and EDF 2 at 5.09 dB/m and 7.28 dB/m, respectively, have been demonstrated. The system was designed based on a single ring cavity by employing a graphite flakes saturable absorber (SA) with 23.82% of saturable absorption. The experimental results showed that a wide-band tunable covering from 1544 nm to 1560 nm and 1552 nm to 1570 nm for EDF 1 and EDF 2, respectively, could be achieved. The EDF 2 was observed to be the best gain medium due to the conventional wavelength band at C band and L band region.

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