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GENERATION OF Q-SWITCHED THULIUM-DOPED FIBER LASER (TDFL) USING DIFFERENTSATURABLE ABSORBERS

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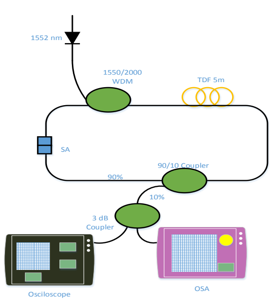
Graphical abstract



Abstract

A Q-switched Thulium-doped Fiber Laser (TDFL) operating at approximately 2 μm wavelength is successfully generated by using four different saturable absorbers (SAs) which are nitrogen-doped graphene in PVA (NG:PVA), nitrogen-doped graphene in PEO (NG:PEO), single-walled carbon nanotube in PVA (SWCNT:PVA), and high pressure carbon monoxide carbon nanotube in PVA (CNTHiPCO:PVA). The SAs integrated in the cavity were able to provide the real saturable absorption in modulating the intra-cavity losses. SWCNT gives the best results with the highest repetition rate and lowest pulse width of 57.45 kHz and 1.958 nJ correspondingly as compared to the other three SAs.

Keywords: Saturable absorber, Q-switched

1.0 INTRODUCTION

In recent years, progress on the light source at longer wavelength has been made in order to suffice the demands and high dense capacity of data users. Currently, the backbone of high-capacity lightwave communication systems are all based on the erbium-doped fiber (EDF) system[1]. This includes erbium-doped fiber amplifiers (EDFAs) as optical repeaters in the transmission links[2]. In traditional practice of optical communication system, optoelectronic regenerators are used between terminals to convert incoming optical signals to the electrical and then back to the optical domain[1]. To date, tremendous researches and developments in EDFA have contributed much to the society world widely such as far-reaching transmission, high-speed internet, and many other benefits. Erbium (Er) as the active gain medium in the system is able to emit powerful laser at wavelength in 'eye-safe' 1.55 μm region[3]. This is one of the most criteria that makes Er^{3+} as the successful candidate especially in the optical communication society due to the wide bandwidth availability after the numerous techniques proposed to extend the operation to S-band and L-band[3].

Nevertheless, due to high demanding applications that in needs of wider and longer wavelength, researches on thulium-doped fiber laser (TDFL) to work on 2 μm[4] spectral region have been progressively conducted[4, 5]. 2 μm is also known as the 'eye-safe' window [6] despite of 1.55μm. The 2 μm window is estimated to cover the range from 1800 nm to 2100 nm which is about 300 nm bandwidth [7, 8]. TDFL has attracted various applications including medical, light and range detection (LIDAR) [7], military and defense[9], gas remote sensing [10] and also the optical communication due to its ability to emit at 2 μm region [11]. Ultrafast fiber laser [12, 13] is an ultimate invention in the revolution of high power laser. The ability to produce a monochromatic and highly coherent light source has put fiber laser as advantageous over solid state laser in various fields of interests. Other possible traits such as compact, robust, cost-wise [14] and other excellent characteristics have made fiber laser as an alternative high quality beam generation [15, 16].

Q-switched fiber laser is of a great interest in laser technology for its ability to produce high energy pulse[17, 18]. Q-switched fiber laser can be generated by both active and passive methods [7]. In actively Q-switching operation, the modulation of the intracavity loss is being controlled by the external component equipped in the laser cavity such as acousto-optic modulator and electro-optic modulator [19]. Unlikely for passively Q-switching, the Q-factor modulation can be realized by the incorporation of saturable absorbers (SAs) in the laser cavity [20-22]. For instance, such as semiconductor saturable absorber mirrors (SESAMs) [8, 11], carbon nanotube (CNT) [13, 23-26], and graphene-based saturable absorber (GSA) [7, 16, 19, 22, 27-29]. Besides using SAs for the pulse generation, there are other techniques that can be utilized for the application. Such technique that can be demonstrated is non-linear polarization rotation (NPR) [17, 30]. In this technique, a so called artificial saturable absorption is created in the cavity that will induce the pulse generation. Polarization controller (PC) is cascaded in the cavity as to maintain the non-linear polarization of the propagating signal inside the laser cavity. Other than it helps in the generation of pulse, NPR technique is able to produce intensity-dependent optical transmission throughout the process by self-phase modulation (SPM) mechanism. As for CNT based SA, Ahmad et.al reported on the application of multi-walled carbon nanotube (MWCNT) SA in the generation of Q-switched TDFL. It produced of 103.37 nJ pulse energy with 21.67 kHz repetition rate and 7.93 μs pulse width [25]. On the other hand, the use of single-walled carbon nanotube has also been reported in the generation of Q-switched EDFL with 29.4 kHz repetition rate, 11.2 μs pulse width, and 93.9 nJ pulse energy [24]. Besides having CNT as SA, graphene-based SA also is popular in the pulse laser system. Graphene oxide (GO) has been applied in the Q-switched TDFL with 16.0 kHz repetition rate, 9.8 μs pulse width, and 18.8 nJ pulse energy [7]. Sobon et.al made use of the GO to generate 115 kHz repetition rate, 1.85 μspuls width, and 125 nJ pulse energy of Q-switched EDFL [19]. Besides having GO as SA, Lu et.al generated the Q-switched TDFL with only graphene as SA with 128 kHz repetition rate and 260 nJ pulse energy [29].

In the conducted experiment, four different SAs have been used instead of one kind to observe the performance of the SAs. The experiment has been focused on achieving and generating Q-switched TDFL with 'real' saturable absorption. The 'real' saturable absorption is created by the SAs used to modulate the intra-cavity loss of the laser system.

2.0 EXPERIMENTAL SETUP

The experimental setup is schematically shown in Figure 2 where the fiber laser system is in a ring cavity configuration. The purpose of setting up the ring cavity is to have a unidirectional oscillation. This system consists of 5 meter length of thulium-doped fiber (Nufern, SM-TSF-9/125) as the active gain medium where this TDF has 9 μm and 125 μm core/cladding diameter. The TDF used has the highest peak absorption of 27 dB/km at 793 nm wavelength. The high absorption of the Tm^{3+} ions allows the use of the shorter gain medium. The gain medium is pumped by 1552 nm laser diode through the 1550/2000 nm wavelength division multiplexer (WDM). The output of the laser is tapped with the 90/10 coupler. Ninety percent of the output retains in the ring cavity for further lasing oscillations. The ten percent output port is connected to the 3 dB coupler. The means of putting the 3 dB coupler was one of the precautionary steps taken during the experiment. Moreover, readings from both output ports of the 3 dB coupler can be taken simultaneously where the first port is connected to optical spectrum analyzer (OSA, Yokogawa AQ6375) for the spectral analysis and the other port is connected to the oscilloscope (LeCroyWaveJet 352A 500MHz) to observe the pulse train of the Q-switched TDFL operation. The photodetector used is Indium Gallium Arsenide (InGaAs) photodetector (EOT Inc. ET-5010F). In this experiment, four different SAs have been used which are nitrogen-doped graphene in polyvinyl alcohol (NG:PVA), nitrogen-doped graphene in polyethylene oxide (NG:PEO), single-walled carbon nanotube (SWCNT), and HiPCO carbon nanotube (HiPCOCNT). HiPCOCNT is carbon nanotube produced from the process known as High Pressure Carbon Monoxide (HiPCO) process. The SAs were then placed in the TDFL by sandwiching them between two FC/PC connectors. Index matching gel is applied on the ferrule to minimise the reflection that occur in the optical fiber.

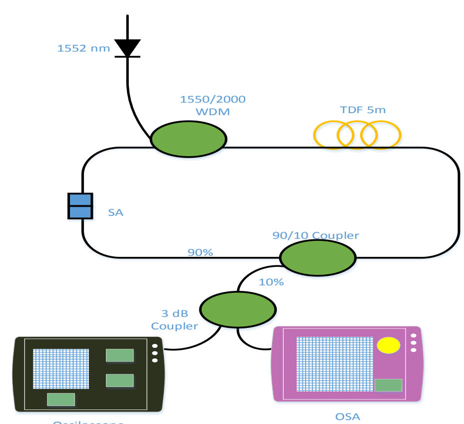


Figure 1 Experimental setup of Q-switched TDFL with 1552 nm pump

3.0 RESULTS AND DISCUSSION

Figure 2a, 2b, 2c, and 2d show the optical spectra of both CW and Q-switched TDFL by using NG:PEO, NG:PVA, SWCNT, and HiPCOCNT as the saturable absorbers respectively. In Figure 2a, the CW laser emission is at 1973 nm wavelength. After the installation of the SA, the operating wavelength has shifted to 1951 nm. In Figure 2b, the Q-switching operation has also made the wavelength shifted from 1970 nm to 1954 nm. On the other hand, in figure 2c, the CW laser has generated dual wavelengths, one is emitted at 1971 nm and the other one is at 1965 nm. During the Q-switching operation, both wavelengths have shifted to around 1932 nm and 1925 nm respectively. For the Q-switching operation in figure 2d, the wavelength has made a shift from 1959 nm to 1954 nm. Besides having the wavelength shifted, these laser systems also were experiencing another effect which is known as self-modulation (SPM) effect.which is one kind of non-linearity that occurred in the optical fiber. The intensity-dependent pulse that propagates in the fiber which the SPM effect is more pronounced to happen, has experienced the wavelength shifted from longer wavelength to a shorter ones or can be said that the frequency shifts from lower to higher frequency. SPM effects can also cause the broadening or narrowing of the spectrum. In many Q-switching operations, and experimentally proven in this experimental works, the Q-switched spectrum broaden. This is due to the constructive interference of the amplitudes, one that is caused by the SPM and the others are the amplitudes which are already present in the pulse. However, the interference can also be destructive whereby the spectrum will get narrowed. In this work, the amplitudes generated from the SPM mechanism interfered constructively with the amplitudes of the light waves in the pulse.

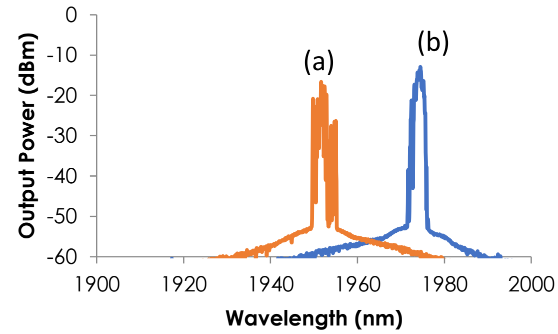


Figure 2a Optical spectrum for (a) Q-switched (b) CW laser, using NG in PVA as SA.

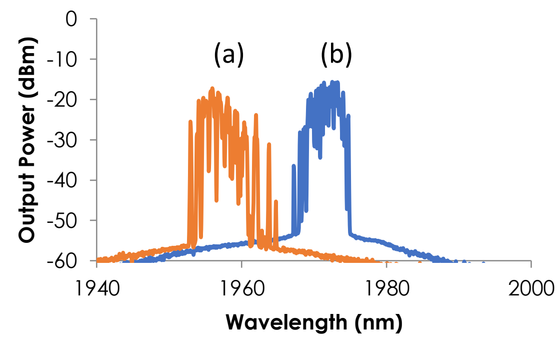


Figure 2b Optical spectrum for (a) Q-switched (b) CW laser, using NG in PEO as SA.

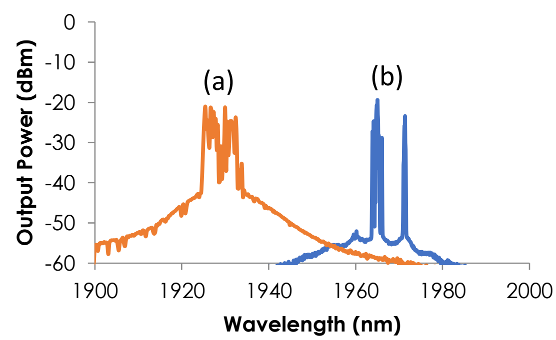


Figure 2c Optical spectrum for (a) Q-switched (b) CW laser, using SWCNT as SA.

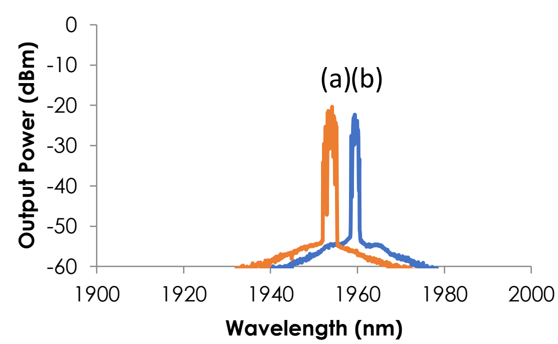


Figure 2d Optical spectrum for (a) Q-switched (b) CW laser, using HiPCOCNT as SA.

Figure 3a, 3b, 3c, and 3d are the results of output power and pulse energy of the demonstrated Q-switched TDFL as functions of pump power. Aforementioned, these fiber laser systems are all intensity-dependent, therefore the output power is increasing directly proportional to the pump power. For Figure 3a, the Q-switching lasing threshold started at 282 mW pump power and it increased until the pump power reaches its maximum operating value at 336 mW. After this point, the pulse is no longer available. The output power of the Q-switched TDFL is increasing linearly with the increasing of the pump power where the maximum value obtained is 0.45 mW. The secondary axis represents the pulse energy. The pulse energy for the threshold value is 7.56 nJ. It reaches its highest value at pump power of 308 mW with energy of 9.57 nJ. At pump power of 322 mW, the pulse energy recorded was 8.81 nJ. Then, at the maximum pump power, the pulse energy increases back with a value of 9.07 nJ. A slight fluctuation indicates the generation of another pulse in the next round-trip in the cavity. This phenomenon explains why the pulse energy is independent of pump power. Figure 3b depicted the output power and pulse energy of NG:PEO based Q-switched TDFL as functions of pump power. At this time, there were ten values recorded and the trends for both parameters are significant. The lasing threshold for the Q-switched TDFL is 280 mW with output power of 0.44 mW. The maximum output power recorded is 1.04 mW at 330 mW. On the secondary axis, the pulse energy for the pulse laser at the threshold is 24.34 nJ. At the maximum pump power for the Q-switching operation, the pulse energy recorded is 31.11 nJ. Figure 3c on the other hand shows the graph of Q-switched TDFL with SWCNT as the SA. The lasing threshold started at 472 mW with output power of 0.46 mW. During the lasing processes, the output power increased linearly with the increasing of the pump power. The highest output power reported to be 0.6 mW at 511 mW pump power. On the other hand, the pulse energy shows a little decrement at 511 mW when the value drops from 10.88 nJ to 10.44 nJ. When more gain is provided to saturate the SAs, that is the energy stored in the cavity is higher, the pulse energy seems to increase. The Q-switching operation is stable and pulse generating activities are on the track. Upon reaching a certain value which can be said as the saturation point, the value of pulse energy is decreasing and there is insufficient time for the active ions in the SAs to decay back to the ground state before it gets depleted. The absorption of the SAs is subsequently saturates and the pulse is then released. A decrement of 0.44 nJ in the pulse energy is caused by the atomic decay in SWCNT to further generate another energetic pulse in the next round-trip. Figure 3d reported on the performance of the Q-switched TDFL with HiPCOCNT as SA. The Q-switched lasing threshold started at 457 mW which produced an output of 0.32 mW. The highest pulse energy recorded was 9.59 nJ at 463 mW. The system seems to be not stable after four readings have been taken. This would be the possibility that the SA could no longer act as a Q-switcher in the system. The pulse energy decreases drastically to some extent until the pulse is no longer available.

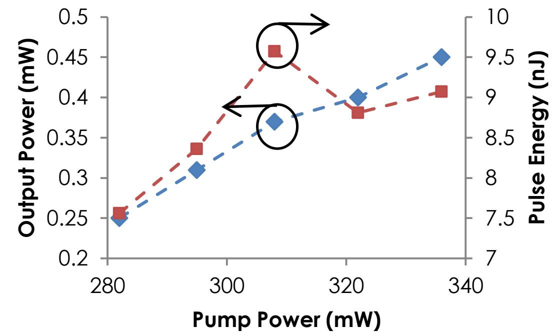


Figure 3a Output power and pulse energy as functions of pump power for NG:PVA as SA

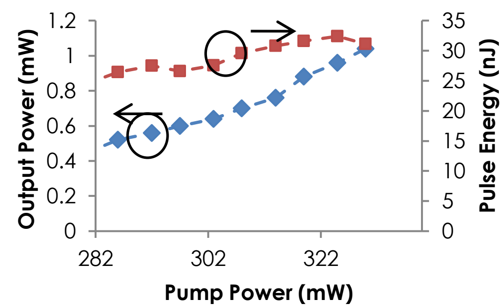


Figure3b Output power and pulse energy as functions of pump power for NG:PEO as SA

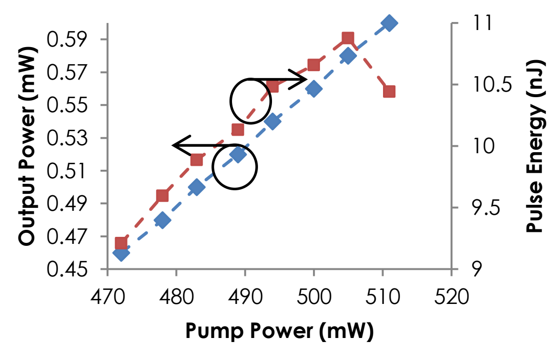


Figure 3c Output power and pulse energy as functions of pump power for SWCNT as SA

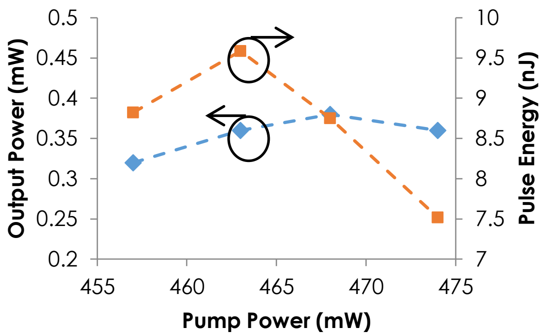


Figure 3d Output power and pulse energy as functions of pump power for HiPCOCNT as SA

Figure 4a, 4b, 4c, and 4d show the relationship of the repetition rate and pulse width as both are functions of pump power. Repetition rate is dependent of pump power; therefore as the pump power is increasing, the repetition rate will be likely increasing. In Q-switching operation, cavity length has no influence on the repetition rate. For the pulse width, this parameter is inversely proportional to the pump power; therefore the value will be decreasing as the pump power is increased throughout the lasing oscillation in the cavity. It is important in the Q-switching operation to achieve shorter pulse duration for it is one of the significant characteristics of ultrafast laser system. In Figure 4a, the highest frequency reported for this Q-switched TDFL is 49.6 kHz at pump power of 336 mW. The value is increasing from 33.06 kHz to 49.6 kHz with 16.54 kHz range. The shortest pulse width recorded is 4.58 μs at the maximum operating pump power. For Figure 4b, the repetition rate at the lasing threshold is 18.08 kHz and it kept increasing until it reaches the maximum pump power with a value of 33.43 kHz. It shows about 15.35 kHz increment range. The shortest pulse width reported is 3.205 μs at the maximum output power. From the result obtained, the NG:PEO SA is able to generate and retained a stable pulse with frequency that can be tuned from 18.08 kHz to 33.43 kHz. With further increase of the pump power, that is above 330 mW, the NG:PEO SA can no longer maintain the stability and as the result, the pulse train disappear. The NG:PEO SA is said to has reached its damage threshold. The performance of Q-switched TDFL with SWCNT as SA is presented in Figure 4c. At the lasing threshold, the repetition rate recorded is 49.94 kHz. This value increases until the pump power reaches its maximum operating power at 511 mW. At this point, the highest repetition rate recorded is 57.45 kHz. It shows about 7.51 kHz increment range. The shortest pulse width recorded is 1.958 μs at the maximum operating pump power. This value of the shortest achieved in the application of the four SAs. Figure 4d, shows the HiPCOCNT Q-switched TDFL performance. The repetition rate recorded at the lasing threshold was 36.27 kHz. The frequency can be tuned from 36.27 kHz until 47.88 kHz with 11.61 kHz in range. The pulse width on the other hand shows a little decrement in the value. At the lasing threshold, the pulse width recorded was 2.97 μs. This value was decreasing slowly until the shortest value recorded was 2.595 μs at 463 mW pump power. There was no obvious decrement of the pulse duration in the experiment. Figure 5 represents the pulse trains of the Q-switched TDFL generated with the respective SAs. In pulsed laser system, it actually periodically emits high energetic pulses in ultra-short time duration. Therefore, the pulse train of any Q-switched laser system represents the energy emitted with the emission time. The narrow the pulse envelopes to each other indicate the shorter time duration and finally, more energetic the pulse is which means more energy it carries

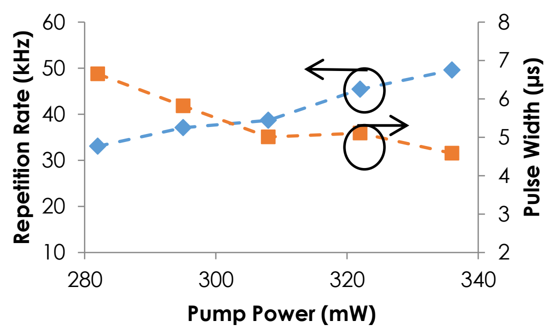


Figure 4a Repetition rate and pulse width for NG:PVA as SA

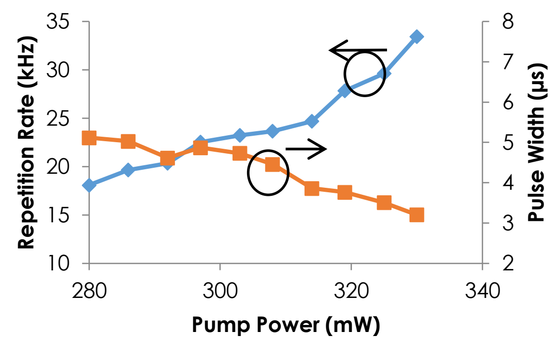


Figure 4b Repetition rate and pulse width for NG:PEO as SA

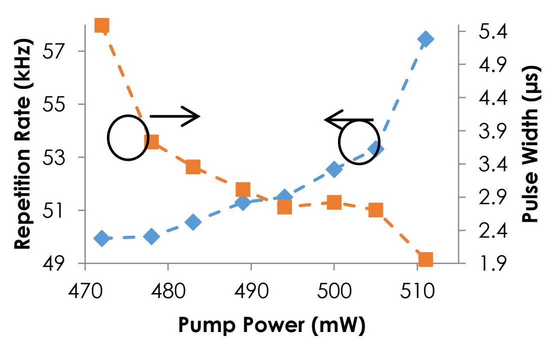


Figure 4c Repetition rate and pulse width for SWCNT as SA

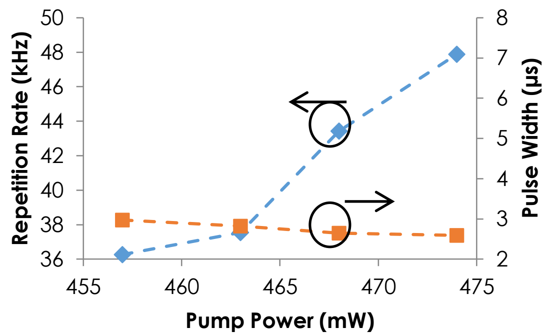


Figure 4d Repetition rate and pulse width for HiPCOCNT as SA

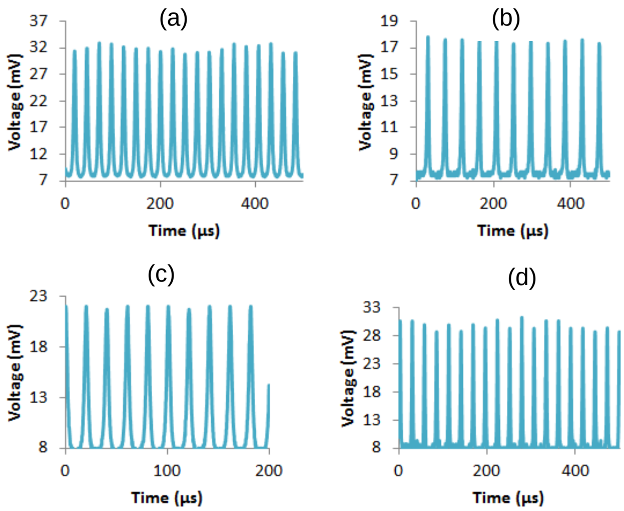


Figure 5 Pulse train of Q-switched TDFL ; (a) NG:PVA, (b) NG:PEO, (c) SWCNT, (d) HiPCOCNT

5.0 CONCLUSION

As a conclusion, firstly, Q-switched TDFL is successfully generated with the incorporation of SA in the laser cavity. Different SAs yielded different value of repetition rate and pulse width. The SAs incorporated in the cavity were able to provide the real saturable absorption in modulating the intra-cavity losses. Among the four SAs investigated, it is shown that SWCNT yielded the best results. Secondly, SWCNT Q-switched TDFL was identified to have the highest repetition rate and lowest pulse width with a value of 57.45 kHz and 1.958 nJ respectively among the four SAs applied. These features are important to indicate the characteristics of pulse laser. This shows that CNT is able to produce pulse laser with higher frequency and shorter pulse width. On the other hand, NG:PEO Q-switched TDFL was identified to have both highest output power and pulse energy. The values recorded were 1.04 mW and 32.4 nJ respectively. Again, in comparison to the CNT-based SA, Graphene-based SA has the potential to generate high output power and pulse energy in the Q-switched TDFL system. Different SAs performed uniquely in their very own ways. There will be applications that require shorter pulse duration with high pulse energy and vice versa. Any applications due to specific requirement can be achieved with different SAs that constructively meet the needs.

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