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Passively Q-switched erbium doped fiber laser based on graphene and carbon nanotube saturable absorbers

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ABSTRACT

A passively Q-switched erbium-doped fiber laser (EDFL) was experimented on by employing graphene, single walled carbon nanotubes (SWCNT) and multi-walled carbon nanotube (MWCNT) saturable absorbers (SA). The SA film was obtained by embedding the graphene, SWCNT and MWCNT into polyvinyl alcohol (PVA). The graphene SA was prepared by dipping a PVA thin film into the graphene solution while carbon nanotubes SAs were prepared using the casting method and placed in the ring cavity to produce a stable pulse laser. Graphene, SWCNT and MWCNT SAs were operating at wavelengths of 1558.92 nm, 1557.98 nm and 1558.51 nm, respectively, whereas the continuous wave was 1560.72 nm at the input pump power of 56 mW. The pulse energy, output power, repetition rate and pulse width were compared in graphene, SWCNT and MWCNT SAs. The shortest pulse width retrieved in graphene, SWCNT and MWCNT were 3.90 µs, 3.62 µs 4.43 µs and produced at the repetition rate of 115.00 kHz, 130.70 kHz, and 89.13 kHz, respectively. In comparison to graphene and SWCNT SAs, MWCNT SAs exhibit the best performance in terms of output power of 2.19 mW and high pulse energy of 24.57 nJ in passively Q-switched EDFL.

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1. INTRODUCTION

One example of high-performance lasers is the Q-switched fiber laser, which can be realized from the Q-factor of the laser [1], [2]. Because of their high peak power, Q-switched lasers are frequently utilized in material processing [2] cosmetics, tattoo removal [3], range finding, optical sensor medicine and data storage industries [4]-[6]. Active and passive Q-switching are two methods for achieving Q-switching [7], [8]. The active Q-switching method needs an extra device, namely, an electro-optic or acousto-optic device [1], [9], [10], whereas, the passive Q-switching method does not require those two devices. However, it does necessitate saturable absorbers (SA) that are cost-effective to manufacture and compact in size [11].

Artificial and real SA are two different types of Sas [12]. The artificial SAs, namely, nonlinear polarization rotation (NPR) [6], nonlinear optical loop mirror (NOLM), require continuous maintenance in the cavity [12]. However, placing a real SA is considered effective and most appropriate to obtain high energy pulses from a laser cavity by modulating the intra cavity losses [12]. Graphene [13], [14] transition metal dichalcogenides (TMDs) [15], transition metal oxides (TMOs) [16], [17] carbon nanotubes (CNT) [18], [19] topological insulator (TIs) [20], PbS quantum dots (QDs) [6] and black phosphorus (BP) [21], are some of the examples of real SAs. Among the above mentioned SAs, still carbon-based SA is in high demand due to its superior performance.

Simple fabrication [22], low cost [2], [10], easy to install [12], zero band gap [23], ultrafast recovery time [13], broad bandwidth [12], high damage threshold [18], [24], wide waveband absorption, and excellent electrical, optical properties [13] are some of the advantages of using carbon-based SAs. Due to its zero bandgap, graphene has a wider operating bandwidth than CNT [23]. Because of the higher mass density of the multi-walls, multi-walled carbon nanotube (MWCNT) outperform single walled carbon nanotubes (SWCNTs). MWCNTs outperform SWCNTs in terms of mechanical strength and thermal stability [25].

In this research, passively Q-switched erbium-doped fiber lasers (EDFLs), which incorporate carbon-based SAs namely, graphene and carbon nanotubes (SWCNT and MWCNT) has been used to obtain high energy pulse. Three SAs are placed one by one in between two fiber ferrules, with no changes to the experimental design to produce pulse waves in the ring cavity. The output signal parameters notably, output power, pulse energy, pulse width and repetition rate have been compared with each individual SAs. Although a few experiments have been conducted out employing carbon-based SA. However, no single study has compared the output values of carbon-based SAa, namely graphene, SWCNT and MWCNT by incorporating with polyvinyl alcohol (PVA) under the same experimental setup.

2. RESEARCH METHOD

In this experiment, the thin film and polymer composite methods (sandwich structure) have been used to fabricate all three SAs. It is important to prepare PVA solution as a host polymer because of its excellent film-forming [26], very high flexibility [27] water-solubility, transparency, non-toxicity and high durability [16]. A common experimental design as shown in Figure 1 has been prepared to compare the output values of all three SAs and identify the best performing carbon-based SA in a same condition.

2.1. Experimental design

Figure 1 shows the schematic configuration of the passively Q-switched EDFL. The cavity consists of a 980/1550 nm wavelength division multiplexer (WDM), gain medium of 1.7 m EDF with numerical aperture (NA) range of 0.23-0.26 and an isolator to ensure no backward reflection will occur. The polarization controller (PC) is used to adjust the birefringence of the polarization mode of oscillating light for the Q-switching and laser operations. A 95/5 output coupler is connected in the cavity where 95% of light is fed back into the cavity, while the other 5% is characterized as laser output. The core and cladding diameter of the EDF is 6.3 µm and 125 µm, respectively. The fabricated SA was placed between two fiber ferrules using a connector. The EDF was pumped by a 980 nm laser diode via WDM. The spectra of the EDFL with and without SA were inspected by using the optical spectrum analyzer (OSA). The output pulse was inspected by using an oscilloscope (OSC). An optical power meter (OPM) was also used to measure the output power.

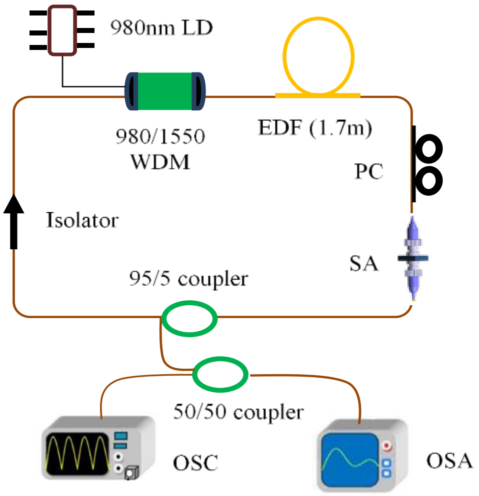


Figure 1. Experiment setup of the passively Q-switched EDFL

2.2. Fabrication of saturable absorber

The graphene SA was prepared by using the commercialized ultra-high N-Butyl acetate concentration graphene dispersion (Graphene supermarket CGD-100 ml, average thickness-7 nm) as a simple and cost-effective dip-coating method as shown in Figure 2. The PVA thin film was dipped into the graphene solution for 30 seconds. The thickness, width, and length of PVA thin films were 50 µm, 1.5 cm, 3 cm. The volume of the graphene solution was approximately 2 ml. Then, the composite PVA-graphene solution was decanted into a petri dish and kept in a dry area at ambient temperature for 48 hours to develop the graphene film.

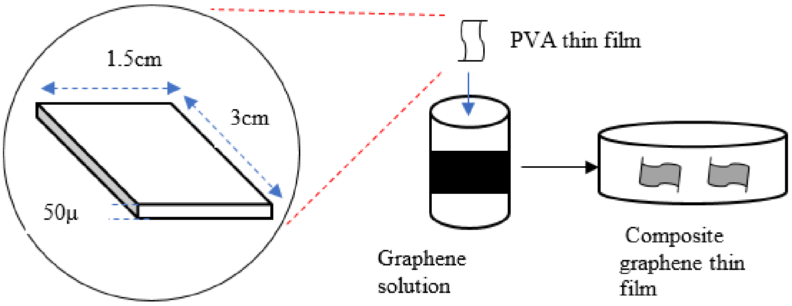


Figure 2. Formation of graphene SA

The fabrication of CNT SAs are depicted in Figure 3. The volume of 250 ml deionized (DI) water was mixed with 2.5 mg sodium dodecyl sulphate (SDS) and stirred for one hour. Then X ml of deionized-sodium dodecyl sulphate (DI-SDS) mixer solution was mixed with Y mg of CNT powder and stirred for 24 hours. Table 1 shows the weight of the CNT powder and the DI-SDS mixer solution. After stirring the solution, it was sonicated for 24 hours.

Table 1. CNT powder with DI-SDS mixer solution

	DI-SDS mixer solution (X ml)	Weight of CNT powder (Y mg)
SWCNT	40	4.0
MWCNT	45	4.5

Afterwards, the PVA solution (1g PVA+120 ml DI water) was mixed with both CNT mixer solutions separately in the ratio of 1:1 and sonicated for 72 hours. The final solution was poured into a petri dish for two days and left to dry. The thickness of both SWCNTs and MWCNT were 13.9 µm and 32.5 µm respectively.

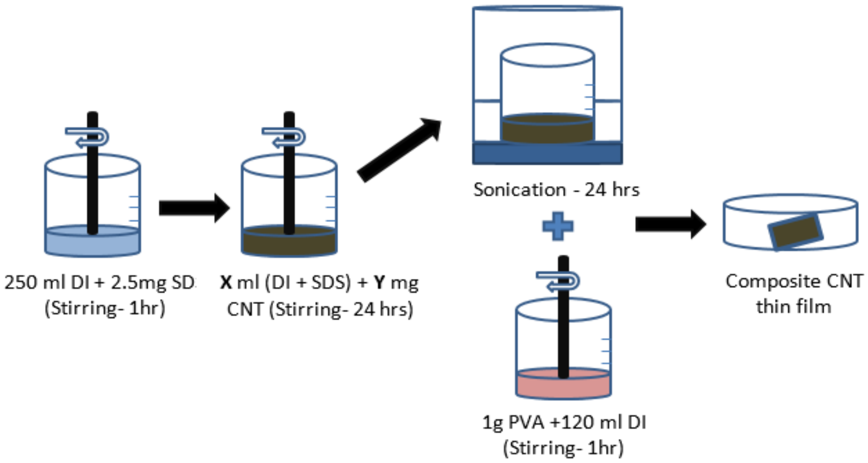


Figure 3. Fabrication of thin film CNT SA

Once the three SAs were prepared, a small portion of thin film SA around 1×1 mm was placed alternately in the cavity to form the SA in 50 cm diameter of ring cavity as shown in Figure 4. The sandwiching was done using a matching gel index. In this experiment, the SA was placed between the polarization controller (PC) and gain medium.

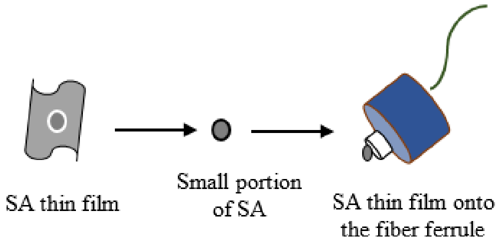


Figure 4. Sandwiching SA onto the fiber

3. RESULTS AND DISCUSSION

In this chapter, we have changed the SA one by one in the same fiber laser cavity and compare the output values. The input pump power had been gradually increased for each SA to obtain a stable pulse in the cavity. The continuous wave lasing in the ring cavity was at 54 mA of pump power. The output spectrum of the EDFL is shown in Figure 5 with and without the SA via a 980 nm pump laser for all three SAs. Figure 5 shows that the passively Q-switched EDFL starts the operation at a wavelength of 1558.92 nm after inserting a piece of graphene SA inside the ring cavity, whereas 1558.51 nm and 1557.98 nm for SWCNT and MWCNT. The average optical output power for graphene, SWCNT and MWCNT are -7.02 dBm, -25.38 dBm and -5.2 dBm, respectively.

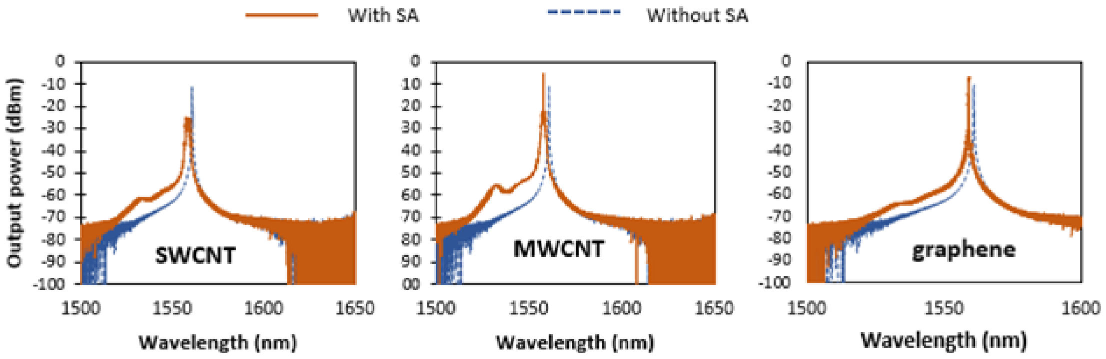
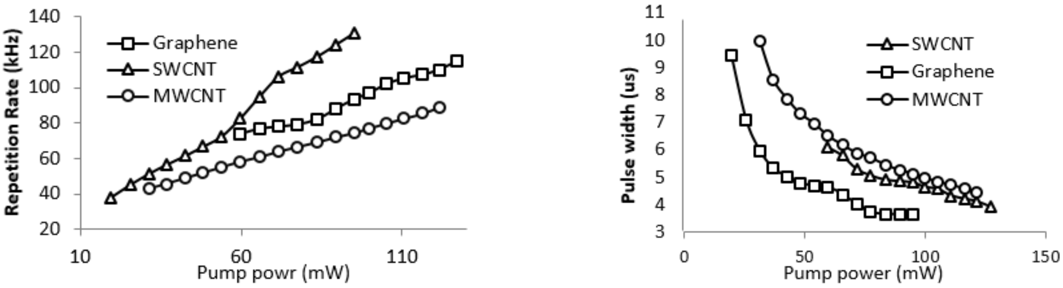


Figure 5. Output spectrum of EDFL with and without SA

3.1. Comparing output values by varying the SAs

First of all, stable pulse train was checked in the oscilloscope by varying the input pump power for each SA. The stable pulse train obtained throughout the varying input pump power of graphene Q-switched EDFL is between the range of 59.6-127.1 mW. The stable pulse train for SWCNT and MWCNT are between the input pump power range of 19.4-95 mW and 31.3-121.5 mW, respectively. While observing the stable pulse, the repetition rate and pulse width values were recorded and plotted in a graph.

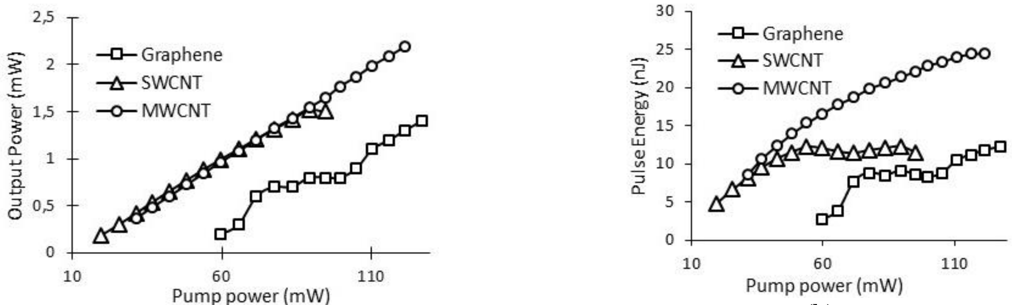
In Figure 6, the output comparison of repetition rate and pulse width of graphene, SWCNT and MWCNT SA are shown. Figure 6(a) shows the repetition rate while Figure 6(b) shows the pulse width of the Q-switched EDFL. In terms of repetition rate, SWCNT Q-switched fiber laser received the highest repetition of 130 kHz and lowest pulse width of 3.62 µs at the pump power of 95 mW. MWCNT Q-switched EDFL received the repetition rate of 89.13kHz and pulse width of 4.43 µs at its highest pump power of 121.5 mW, whereas graphene Q-switched EDFL received the repetition rate of 115 kHz and pulse width of 3.9 µs at its highest pump power of 127.1 mW. Because of their intrinsic saturable absorption properties and ultrafast recovery time, SWCNTs have shown promise for Q-switched fiber lasers.



(a) (b)

Figure 6. Comparision of (a) repetition rate and (b) pulse width of graphene, SWCNT and MWCNT

In Figure 7, the output power comparision and pulse energy comparision of graphen, SWCNT and MWCNT SAs are shown. Figure(a) shows the output power (mW) for the three SAs while varying the input pump power. The maximum output power for graphene EDFL is 1.4 mW, whereas 1.52 mW and 2.19 mW for SWCNT and MWCNT Q-switched EDFL, respectively. Figure(b) shows the comparision the output pulse energy (nJ) for the three SAs in the same Q-switched EDFL, MWCNT Q-switched EDFL received the highest pulse energy of 24.57 nJ at pump power 121.5 mW whereas, graphene and SWCNT Q-switched EDFL received 12.17 nJ at pump power 127.1 mW and 12.24 nJ at pump power 89.3 mW, respectively as shown in Figure(b). The ultrafast pulse generation occurs due to the broad diameter in MWCNT SA.



(a) (b)

Figure 7. Comparision of (a) output power and (b) pulse energy of graphene, SWCNT and MWCNT

Table 2 shows overall performance namely repetition rate, pulse width, pulse energy and Output power. When MWCNT is used as SA in the same Q-switched fiber laser ring cavity, we received the highest pulse energy and output power of 24.57 nJ and 2.19 mW respectively. In terms of repetition rate and pulse width, SWCNT receive the best output performnce of 130 kHz and 3.62 µs.

Table 2. Comparison of graphene and CNTs SA

Saturable Absorber	Repetition Rate (kHz)	Pulse width (µs)	Pulse Energy(nJ)	Output power (mW)
Graphene	115	3.9	12.17	1.4
SWCNT	**130**	**3.62**	12.24	1.52
MWCNT	89.13	4.43	**24.57**	**2.19**

4. CONCLUSION

In summary, we have successfully demonstrated passively Q-switched EDFL by utilizing graphene, SWCNT and MWCNT SAs. In comparison to graphene and SWCNT-based Q-switched EDFL pulse lasers, MWCNT-based Q-switched EDFL pulse lasers achieved the maximum output power of 2.19 mW and pulse energy of 24.57 nJ. When compared to graphene and MWCNT SAs, SWCNT-based Q-switched EDFL offers the best performance in terms of pulse width and repetition rate. SWCNT SA has a pulse width of 3.62 µs and a repetition rate of 130 kHz, respectively.

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