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Passively Q-switched of EDFL employing multi-walled carbon nanotubes with diameter less than 8 nm as saturable absorber

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Abstract. The paper demonstrates passively Q-switched erbium-doped fiber laser implementing multiwalled carbon nanotubes (MWCNTs) based saturable absorber. The paper is the first to report the use of the MWCNTs with diameter less than 8 nm as typically, the diameter used is 10 to 20 nm. The MWCNTs is incorporated with water soluble host polymer, polyvinyl alcohol (PVA) to produce a MWCNTs polymer composite thin film which is then sandwiched between two fiber connectors. The fabricated SA is employed in the laser experimental setup in ring cavity. The Q-switching regime started at threshold pump power of 103 mW and increasable to 215 mW. The stable pulse train from 41.6 kHz to 76.92 kHz with maximum average output power and pulse energy of 0.17 mW and 3.39 nJ are produced. The shortest pulse width of 1.9 μs is obtained in the proposed experimental work, making it the lowest pulse width ever reported using MWCNTs-based saturable absorber.

1 Introduction

As an alternative to solid state laser, ultrafast fiber laser has been the centre of attention these past few years. Q-switching techniques in generating pulsed laser enable shorter pulse duration as well as higher peak power as compared to mode-locked regime [1]. Passive modulation in Q-switching operation is preferred over the active one due to its simplicity and compactness [2]. Saturable absorber (SA) is used to modulate the intracavity losses without the aid of any external modulator, hence the simplicity implied. Multiwalled carbon nanotubes (MWCNTs) have its own advantages over other materials for the use as SA for its intrinsic properties. These properties include good thermal stability and mechanical strength [3] besides its versatility in fibre laser configurations [4]. Saturable absorbers based on carbon nanotubes have been proven to yields fast response time in sub-picosecond [5] as well as wide working range in broadband operation [6] due to its' broad diameter distribution [4]. Carbon nanotubes (CNTs) are comprised of covalently bonded carbon atoms in cylindrical forms. Multi-walled carbon nanotubes are CNTs with more than one graphene cylinders in its structure, making it stronger mechanically, thermally and spectroscopic-wise [7]. Furthermore, the fabrication of MWCNTs is comparably simpler than other reported SAs. Its multi-walled structure makes it far less sensitive towards environment changes [8].

Following the increased interest in carbon nanotubes, many works have been reported on MWCNT-based passive saturable absorber demonstrating different laser performance in Q-switched regime. The broadband properties of MWCNTs for pulsed laser generation utilized MWCNTs with diameter of 10 to 20 nm had successfully demonstrated at 1 μm [9], 1.5 μm [3, 10] and 2 μm [10] region. A paper reported by Kasim et al. [9] utilizes MWCNTs-polyethylene oxide (PEO) composite as SA in 1 micron region, yielding a maximum of 24 kHz repetition rate and 143.5 nJ of pulse energy operating at central wavelength 1060.2 nm. The shortest pulse width is at 12.18 μs at maximum input pump power of 65.72 mW. Ahmad et al. [3] resides the same MWCNTs-PEO based SA in Erbium-Doped Fiber laser (EDFL), producing a stable pulse train with repetition rates ranging from 4.5 kHz to 20.0 kHz as well as maximum pulse energy of 15.3 nJ and shortest pulse width of 8.8 μs. Meanwhile Ahmad et al. [10] applied MWCNTs-PVA in EDFL to generate maximum repetition rate of 29.9 kHz, maximum average output power of 1.49 mW, pulse energy of 49.8 nJ and shortest pulse width of 3.49 μs. In 2 micron region, polyvinyl alcohol (PVA) is used as the host polymer in a MWCNTs-PVA composite film with the ratio of 1:4. The lasing threshold of the laser is very high at 1591.3 mW, tunable to a maximum of 2100 mW [11].

In this paper, a 1.9 μs of pulse width is produced, which is the shortest ever reported using MWCNTs based passive saturable absorber. The results may be caused by the diameter of the MWCNTs used as the diameter of the carbon nanotubes play an important role in the SA's absorption characteristics during laser generation [12-13].

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2 Material Preparation

The mixture of MWCNTs (diameter of < 8 nm and length distribution ~1 to 2 µm) with a 1% sodium dodecyl sulfate (SDS) in deionized water was ultrasonicated for 1 hour at 50 W to form a homogeneous solution. The solution was then centrifuged at 1000 rpm to remove large particles of undispersed MWCNTs. To prepare the host polymer, 1 g of polyvinyl Alcohol (PVA) (Sigma Aldrich) was dissolved in 120 ml De-ionized (DI) water with the aid of magnetic stirrer at room temperature. A MWCNTs/PVA composite was prepared with the solution ratio of 1:1 and ultrasonicated for several hours. The MWCNTs/PVA solution was poured into a petri dish and left to dry at room temperature for about 48 hours to produce film with thickness of around 50 µm as shown in Fig. 1.

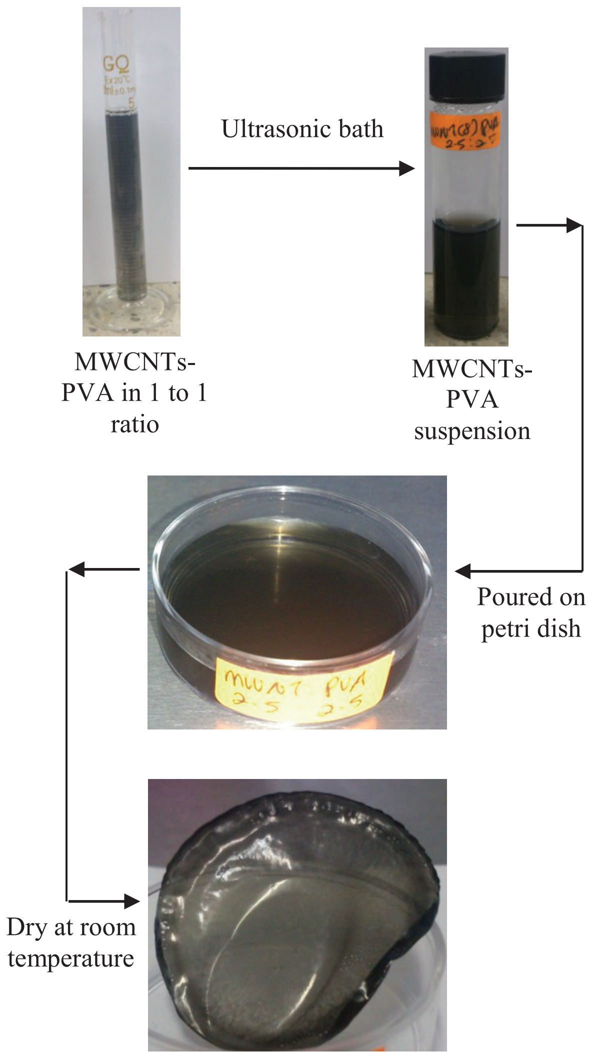


Fig. 1. Preparation of MWCNTs-PVA SA.

3 Experimental Set Up

The experimental setup for the Q-switched EDFL consists of a 1 m long erbium-doped fiber (EDF), a 1480/1550 wavelength division multiplexer (WDM), an isolator, the fabricated SA, and a 95/5 output coupler. The isolator is placed to ensure uni-directional propagation of the light oscillating the cavity. The instrument is arranged in ring configuration as shown in Fig. 2, pumped with a 1480 nm laser diode via the WDM. The output of the Q-switched fiber laser is observed through an oscilloscope (OSC), optical power meter (OPM) and optical spectrum analyser (OSA). The output is fed through a 3 dB coupler from the 5% tapped laser output while the other 95% remains in the cavity.

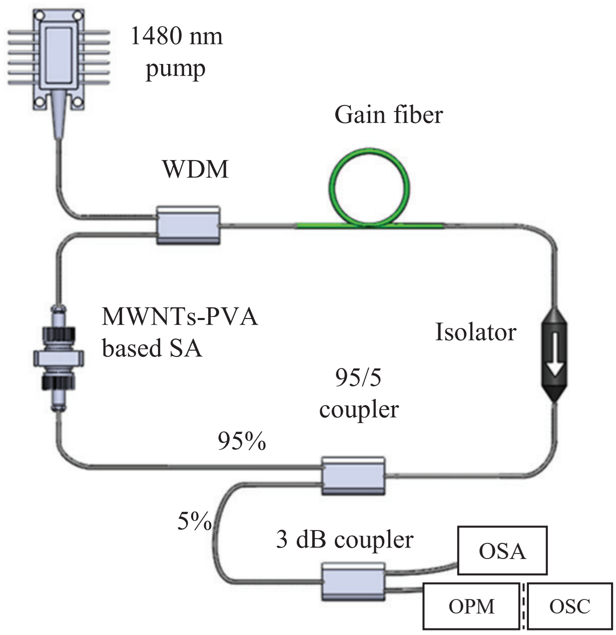


Fig. 2. Schematic configuration of the Q-switched EDFL.

4 Results and Discussions

The EDFL started lasing in Q-switched regime at around 103 mW pump power. The threshold input pump power is considered high compared to other reported works [3, 10], this is due to opaque properties of PVA which when combined with carbon black material, require higher pump power to fully saturate the SA. Beyond the maximum power, the pulse laser is no longer observed. However, reducing the pump power to 215 mW and less enable Q-switching operation to be accomplished again. Fig. 3 shows the central operating wavelength of the laser output of 1558.2 nm at maximum input pump power with 3-dB bandwidth of 0.4 nm. Fig. 4(a), 3(b), 3(c), and 3(d) shows the oscilloscope traces of the pulse generated at four different pump powers which is 131 mW, 187 mW, and 215 mW, with the respective single pulse envelope, respectively. The recorded pulse train shows an acceptable intensity fluctuation when the light propagates in the laser cavity for every cavity round trip. The pulse repetition rate at 215 mW with 76.92 kHz generated the shortest pulse width of 1.9 µs. The proposed works produced the shortest pulse width using MWCNTs based SA in EDFL compared to the reported works in [3,10] and other SAs. For example, the paper reported by Luo et al. [14] using molybdenum disulphide (MoS_2) as SA produced shortest pulse duration of 5.4 µs. Topological insulators as passive saturable absorber was demonstrated using bismuth selenide (Bi_2Se_3) and bismuth telluride (Bi_2Te_3), yielding pulse width of 1.9 µs and 13 µs respectively [15,16].

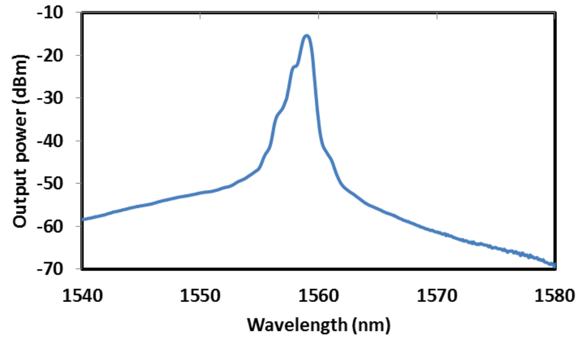
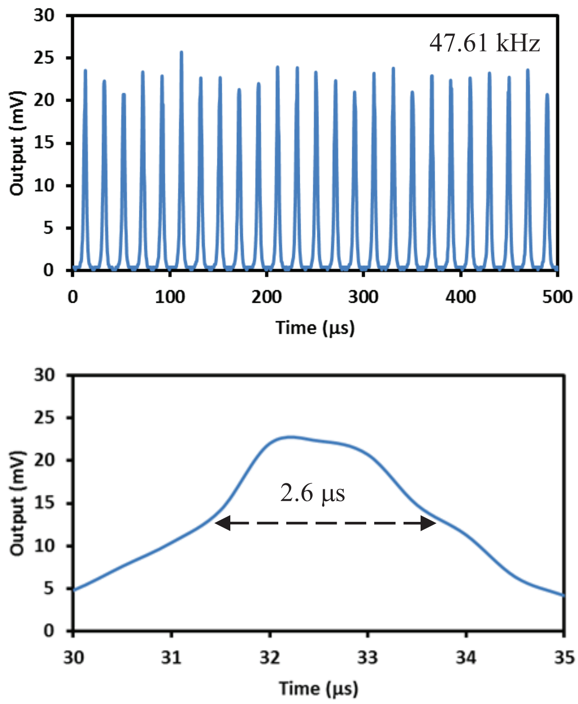
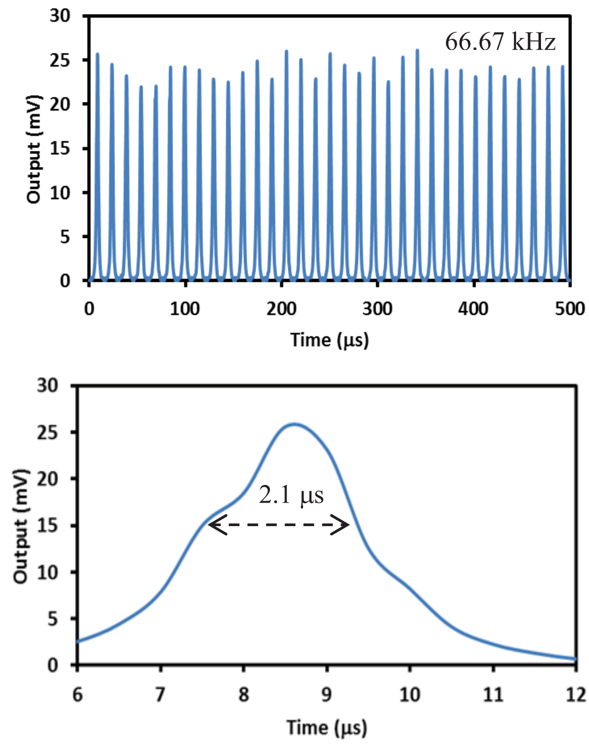


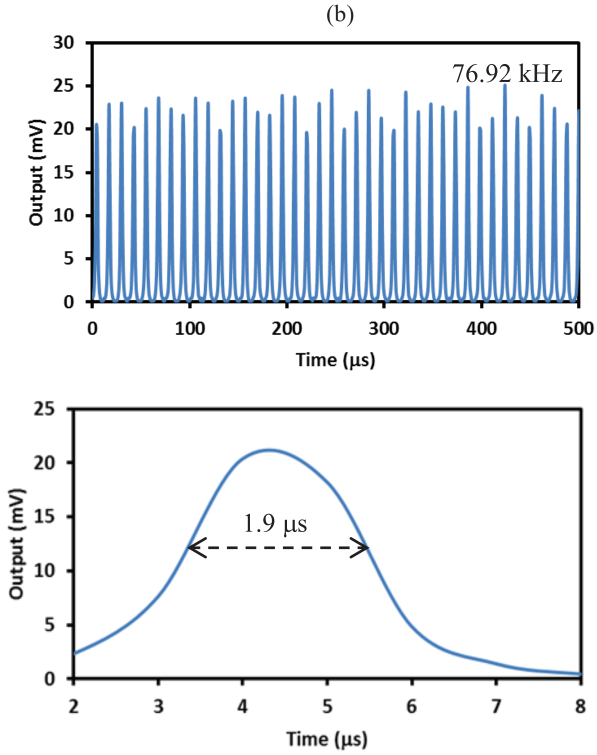
Fig. 3. OSA trace at 215 mW.



(a)



(b)



(c)

Fig. 4. Pulse train at (a) 131 mW, (b) 187 mW, and (d) 215 mW with respective single pulse envelope.

The repetition rate and the average output power of the pulsed laser increases with the increasing pump power. Higher pump power supplied to the cavity means shorter time is taken for the inversion number of the gain medium to reach the threshold, which then resulted in higher calculated peak power [2]. As the pump power is tuned from 103 mW to 215 mW, the repetition rate increases almost steadily from 41.6 kHz to 76.92 kHz. The repetition rate at incident pump power of 215 mW, is highly comparable to other previously reported works on MWCNTs-based SAs [4, 9, 11] [17-19] The average output power of 0.17 mW is obtained at maximum pump power. The relationship between the repetition rate and average output power with respect to the pump power is clearly shown in Fig. 5.

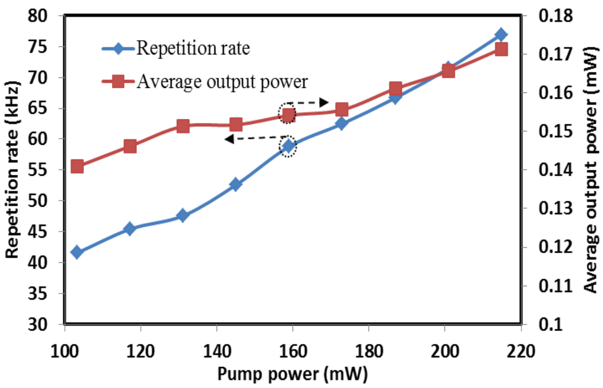


Fig. 5. Pulse repetition rate and average output power versus pump power MWNTs/PVA polymer composite (<8nm).

Fig. 6 shows the pulse width and pulse energy as a function of the pump power. Increasing the pump power makes the pulse width shorter while the pulse energy becomes larger. As the pump power is increased, the energy required for the transition of carriers from the valence band to the conduction band is higher, thus shortening the time taken for the light round trip in the cavity. This in turn contributes to the increasing calculated pulse energy. The pulse width decreases from 3.3 µs to 1.9 µs, while the pulse energy is increased to a maximum of 3.39 nJ with the increment of the pump power from threshold to 215 mW. The characteristics of the proposed Q-switched laser are in agreement with other reported Q-switched lasers [17-20].

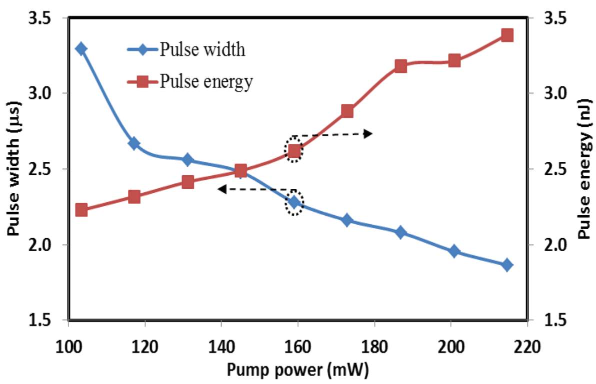


Fig. 6. Pulse width and pulse energy versus pump power MWNTs/PVA polymer composite (<8nm)

4 Conclusion

A stable passively Q-switched EDFL incorporating MWCNT composite polymer thin film with diameter of less than 8 nm as saturable absorber is demonstrated. To the best of our knowledge, the laser performance generated a 1.9 µs pulse width, the shortest pulse duration reported using MWCNTs based SA. The maximum repetition rate of 76.92 kHz is obtained with a maximum of 3.39 pulse energy.

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