Q-Switched Ultrafast TDFL Using MWCNTs-SA at 2 µm Region

M. T. Ahmad, A. A. Latiff, Z. Zakaria, and S. W. Harun

***Abstract*—We demonstrate an ultrafast TDFL Q-switched pulse in 2 µm wavelength using multi-walled carbon nanotubes (MWCNTs) as passive saturable absorber (SA). MWCNTs film is sandwiched between two fibre connectors or patch cords after deposited with index matching gel on the fibre ferrules. Thulium-doped fibre was pumped using 1552 nm source in the ring cavity. The repetition rate for the pulses can be tuned from 13.33 kHz to 21.07 kHz by varying the pump power from 307.5 mW to 371.4 mW. At the maximum power, the pulse generated energy of 87.34 nJ with full-width at half maximum (FHWM) of 8.21 µs.**

***Index Terms*—Multi-walled carbon nanotubes, passive saturabe absorber, Q-switching.**

I. INTRODUCTION

2-micron region lasers are one of the highly interest topic by its diversity of application from material processing, light imaging detection and ranging (LIDAR), biomedical, security and remote sensing [1]-[4]. They can be found using either active of passive methods on Thulium-doped or Holmium-doped fiber lasers [5]-[7]. At the same time, Thulium-doped fibre lasers (TDFL) are becoming interesting topic of research subjects for many applications. TDF generates broader emission spectrum covering near infrared region including 2 microns region [8]-[10].

TDFL also known as 'eye-safe' laser because of the laser characteristic that is highly absorbable by water before it reaching the retina [8]-[11]. Thulium has an excellent performance in 2 micron region. It happens because of the electron radiative emission from 3F4 → 3H6 (Stark level) [8]-[12]. Theoretically, the phenomenon doubled the quantum efficiency when it occurred efficiently [8]-[14].

Q-switched fibre laser branched into two types, that are active Q-switching and passive Q-switching. Passive Q-switched fibre lasers provides more flexibility in the design and do not require additional electronic component in the ring cavity. It was successfully demonstrated by using different kind of saturable absorbers (SAs). There are a lot SAs that been used to generate the laser such as graphene [6], single-walled carbon nanotubes (MWCNTs) [15], [16] and semiconductor saturable absorber mirrors (SESAMs) [17]. However, SESAMs cannot be used widely due to the complexity of fabrication and not cost effective. As a solution, study focusing to give an optimization to MWCNTs as a SA in Q-switched and mode-locked fibre laser in a years back. [18]-[20]. This may cause by the advantages of MWCNTs including high compatibility with fibre optic applications, wide operating bandwidth, fast recovery time and low saturation intensity.

Recently, a new type of carbon nanotubes family was found, multi-walled carbon nanotubes (MWCNTs) [21], [22]. It has attracted attentions in photonic research field especially in nonlinear optic applications due to the cost effectiveness, which will reduce up to 20% – 50% of MWCNTs material. [23] The development of MWCNTs material does not require special techniques or conditions so thus will generate high productivity. MWCNTs are mechanically stronger, thermally stable as well as can absorb more photons energy per nanotubes due to high density of mass at the multi-walls. These feature happen because of the structure of MWCNTs itself, which is a stack form of concentrically rolled graphene sheets. The outer walls will protect the inner walls from oxidation that will damage the walls. This to ensure the thermal and laser damage threshold is higher than SWCNTs. [24], [25] As far as the authors known, there are only few works reported regarding the usage of MWCNTs as saturable absorber in fibre laser application. For instance, Zhang *et al.* [23] employs MWCNTs as saturable absorber for mode locking of neodymium-doped yttrium vanadate (Nd:YVO4) laser. In other work, Q-switched neodymium-doped yttrium aluminum garnet (Nd-YAG) laser is demonstrated using MWCNTs based saturable absorber as Q-switcher.

In this paper, a Q-switched TDFL operating near 2 micron wavelength region is demonstrated using a multi-walled carbon nanotubes SA with polyvinyl alcohol (PVA) 3:2. The SA is fabricated by mixing 250 mg MWCNTs (99% pure with diameter of 10-20 nm and length of 3-30 µm) with 400 ml 1% SDS solution in deionised water and the ultrasonicating it for 30 minutes at 50 W to form a homogeneous suspension solution. The solution was centrifuged at 1000 rpm to remove large particles of undispersed CNT to obtain dispersed suspension that is stable for approximately a month. The SA acts as a passive Q-switcher in the ring cavity. The SA is integrated into ring cavity by sandwiching the film between two fibre connectors, resulting a stable pulse train with 13.33kHz repetition rate, 11 µs pulse width and 57.01 nJ pulse energy at 307.5 mW 1552 nm pump power.

II. EXPERIMENTAL SETUP

Fig. 1 shows the configuration of the proposed Q-switched TDFL using MWCNTs-SA. The setup consists of a 5 m long

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thulium-doped fibre, which is pumped by a 1552 nm laser through a 1550/2000 nm wavelength division multiplexer (WDM), a MWCNTs-SA, and a 10 dB output coupler in a ring configuration. The SA is prepared using a tiny patch of MWCNT film and sandwiching it between two fibre connectors or patch cords (FC/PC), only after depositing index-matching gel onto the fibre ferrule. The insertion loss measured to be around 3.3 dB at 1900 nm. The TDF used in this experiment has a core and cladding diameters of 9 μm and 125 μm respectively while the peak core absorption at 1180 nm and 793 nm for the TDF are 9.3 dB/m and 27 dB/m respectively. The output is extracted via a 10 dB coupler located after the TDF, which 10% of the oscillating light in the cavity is channeled out. The optical spectrum analyser (OSA, Yokogawa AQ6370B) is used to analyse the spectral of the continuous wave (CW) TDFL, while the digital oscilloscope (OSC, Tektronix TDS 3052C) is used to observe the Q-switched output pulse train via a 460 kHz photo detector (PD, PDA50B-EC). The total length of the ring cavity is measured around 14 m.

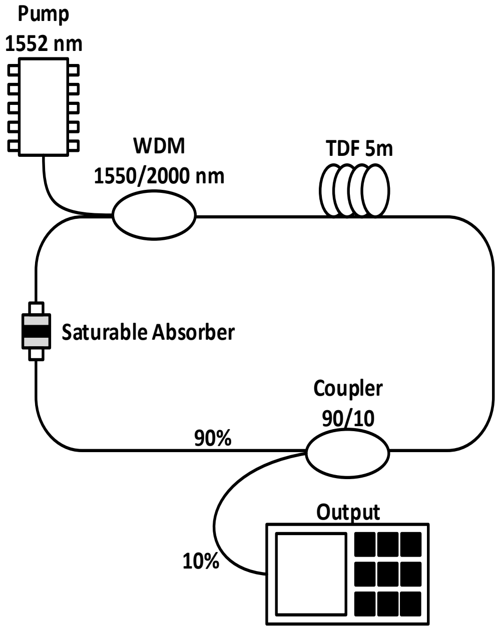

Fig. 1. Q-switched TDFL configuration.

III. RESULT AND DISCUSSION

Fig. 2 shows the Q-switched laser output spectrum obtained from the OSA. With the absence of the SA in the ring cavity, the TDF emits a CW laser with the pump set slightly above threshold of 297 mW. The lasing occurs approximately at 1920 nm. Once the SA is inserted into the ring cavity, the laser starts to turn into a passive Q-switching laser with alteration of pump power to 307.5 mW before the pulse appeared. The laser seems to be shifted to lower wavelength and reduced its power due from the losses generated from the SA. The broadened lasing spectrum determines the laser is improved from the inserted SA.

Fig. 3 shows the efficiency of the ring cavity in terms of input power against output power. It shows that the output power increased linearly when the input power is increase. The figure determined that the cavity is good and have a good potential to generate Q-switching.

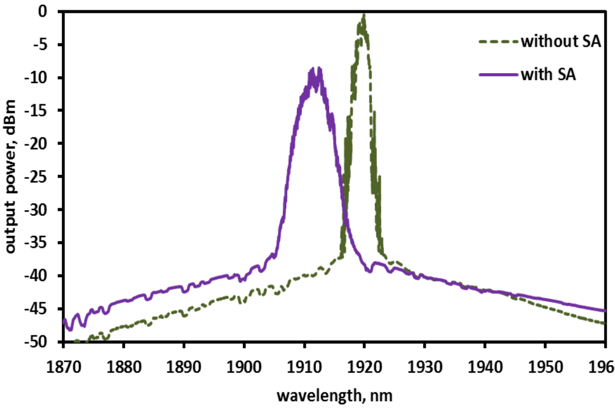

Fig. 2. TDFL threshold at 297 mW.

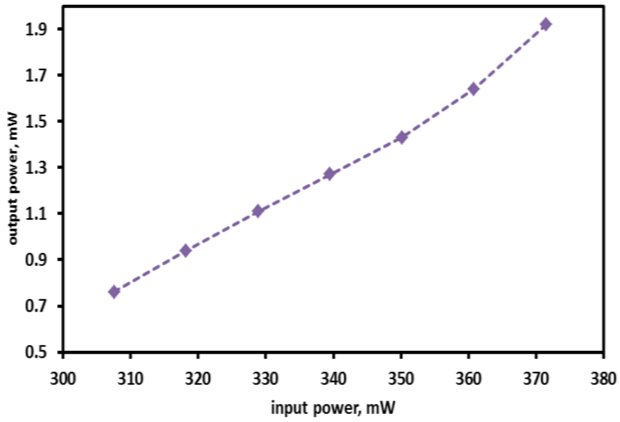

Fig. 3. Power efficiency.

Fig. 4 shows the pulse train from digital oscilloscope trace when the pump power is at the maximum level of 371.4 mW. There is no distinct amplitude modulation at the entire Q-switched envelope in the spectrum, which leads to a knowledge that the self-mode locking effect on the Q-switching is weak. At the pump power of 371.4 mW, a stable passively Q-switching operation occurs with an average output power of 1.92 mW. The repetition rate of the train is 21.07 kHz and the pulse energy is calculated approximately 91.12 nJ. The pulse energy can be improved by reducing the losses in the cavity especially optimizing the insertion loss.

Fig. 5 shows the oscilloscope trace of the pulse envelope zoom into one pulse at the same input power. The figure shows clearer picture of the single pulse picked randomly from the pulse train. As seen in the figure, the pulse width or the FWHM is obtained at 8.21 μs. FHWM is determined by the wide of the pulse at the -3 dB from the peak. Although it named half, due to its relationship with signal processing term, the half power point is determined to be -3 dB.

Fig. 6 shows the repetition rate and pulse width versus the pump power. The readings were taken by increasing the laser diode (LD) current for 20 mA each. As the pump power rises from 307.5 mW to 371.4 mW, the repetition rate increased about 13.33 kHz to 21.07 kHz. This is because when the power increases it also increased the power of the signal, causing the SA to move towards saturation level. The pulse generation is dependent on that saturation level of the SA, which is unpredictable. The pulse width, on the other hand, decreases as the pump power increased, from 11 µS at 307.5 mW, and dropping to 8.21 µS at 371.4 mW. This directly proved the theory that by increasing the power, the repetition rate and pulse width will goes into different direction on each other.

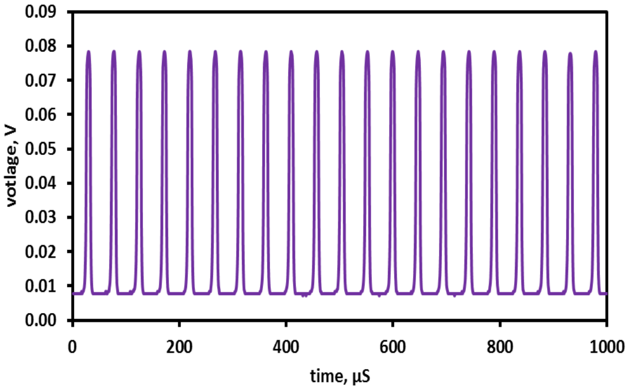

Fig. 4. Q-switched pulse train at 371.4 mW.

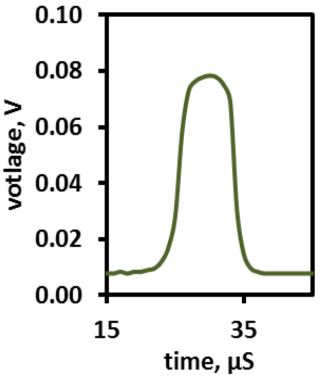

Fig. 5. Single pulse from the train at 371.4 mW.

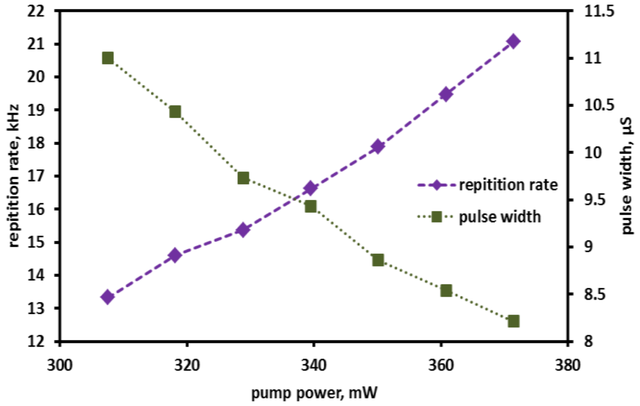

Fig. 6. Effect on repetition rate and pulse width when pump power varying from 307.5 mW to 371.4 mW.

Fig. 7 shows the output power and pulse energy versus the pump power. The output power increase linearly from 0.76 mW to 1.92 mW as the pump power varied from 307.5 mW to 371.4 mW. On the other side, the pulse energy also increases from 57.01 nJ to 87.34 nJ when the pump power is increased. All these results show that multi-walled carbon nanotubes has a big potential to be develop for producing Q-switching laser. The fabrication of the SA is also simple and this will make sure the cost of the laser should be low. It is suitable to be use in applications such as biomedical and environmental sensing because of it low cost and simplicity.

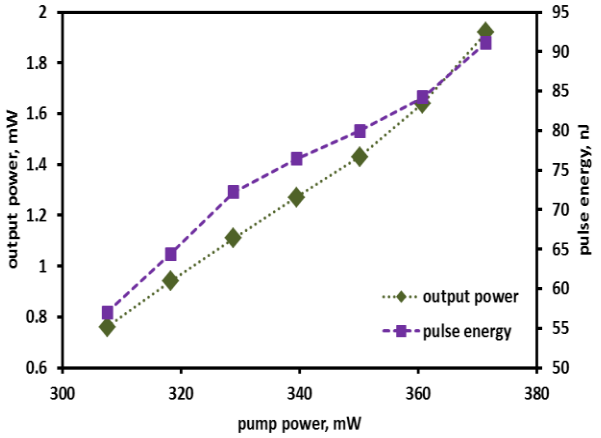

Fig. 7. Pulse energy and output power varying from 307.5 mW to 371.4 mW.

IV. CONCLUSION

A TDFL Q-switched is demonstrated using a MWCNT-based SA. The generated pulses is self-started in a 14 m long ring cavity with repetition rate that can be tuned from 13.33 kHz to 21.07 kHz by adjusting the pump power from 307.5 mW to 371.4 mW. It has a pulse witdh of 8.21 µs and pulse energy of 87.34 nJ at the maximum pump power of 371.4 mW. Q-switched TDFL have a potential to be develop into many application that will contribute to society such as biomedical, remote sensing and material processing. This is due to its simplicity, low cost and eye-safe characteristic.

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