OPTOELECTRONICS AND ADVANCED MATERIALS – RAPID COMMUNICATIONS Vol. 9, No. 9-10, September – October 2015, p. 1104 - 1109

Q-switched Ytterbium doped fiber laser using a multi-walled carbon nanotubes embedded in polyethylene oxide film

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We demonstrate a passively Q-switched Ytterbium-doped fiber laser (YDFL) using a multi-walled carbon nanotubes (MWCNTs) embedded in polyvinyl alcohol (PVA) film as a passive saturable absorber (SA). The SA film is prepared by mixing the MWCNTs homogeneous solution with a dilute PVA polymer solution. It is sandwiched between two FC/PC fiber connectors and integrated into the laser cavity to generate a stable Q-switching pulse operating at wavelength of 1058.6 nm with a threshold pump power of 65.72 mW. The repetition rates of the laser varies from 5.484 kHz to 32.19 kHz as the pump power increases from 65.72 mW to 97.29 mW. The lowest pulse width of 4.2 µs is obtained at the pump power of 69.71 mW while the highest pulse energy of 211.8 nJ is obtained at pump power of 77.75 mW.

(Received August 13, 2015; accepted September 9, 2015)

Keywords: Ytterbium-doped fiber laser, Multi-walled carbon nanotubes/polyvinyl alcohol film, Q-switching, passive Q-switched

1. Introduction

Passively Q-switched fiber lasers with the advantages of compactness and flexibility have attracted much attention in recent years due to their potential applications in laser material processing, remote sensing, telecommunications and medicine [1-4]. They are normally obtained using active approaches by inserting an acoustic-optic or an electro-optic modulator into the laser cavity to generate a short optical pulse through sudden switching of the cavity Q-factor. Recently, passive methods are also widely explored for Q-switching in fiber lasers by utilizing the saturable absorption of optical materials (i.e. saturable absorbers, SAs). In the past, several kinds of SAs such as semiconductor saturable absorber mirrors (SESAMs) [1], carbon nanotubes (CNTs) [2], graphene [3-4] have been successfully used to passively generate Q-switch fiber lasers. Although SESAMs have been well developed and commercially available for the past two decades, they exhibit obvious disadvantages such as complex fabrication, expensive packaging and low damage threshold. The CNTs and graphene absorbers are simpler in fabrication and cheaper than SESAMs, and they operate in a wider wavelength band with a shorter recovery time.

To date, many works have been reported on the use of single-walled carbon nanotubes (SWCNTs) to generate passive Q-switching [2] and mode-locking pulse trains [5]. Recently, a new member of CNTs family, multi-walled carbon nanotubes (MWCNTs) have also drawn the attention of researchers due to their many advantages [6-7]. For instance, the MWCNTs material does not need complicated techniques or special conditions to grow such that its production yield is high. Therefore the production cost of MWCNTs material is reasonably lower than that of SWCNTs material [8]. Additionally, compared with SWCNTs, MWCNTs material has greater mechanical strength, better thermal stability and more photon absorption per nanotube due to higher mass density of the multi-walls. Therefore, the thermal or laser damage threshold of MWCNT should be higher than that of the SWCNTs.

However, there are only a few reported works on the application of MWCNTs material as a SA [7-8]. In this paper, a Q-switched Ytterbium doped fiber laser (YDFL) is demonstrated by using a new developed MWCNTs embedded in polyvinyl alcohol (PVA) film as a passive SA. The laser delivers Q-switched pulses with a repetition rate in a range from 5.484 kHz to 32.19 kHz with the maximum pulsed energy of 211.8 nJ.

2. Fabrication procedure and Raman characterisation of MWCNT-PVA film

The MWCNTs PVA SA used in our experiment is prepared as follows. First, the functionalizer solution is prepared by disolving 4 g of sodium dodecyl sulphate (SDS) in 400 ml of deionized water. The diameter of the MWCNTs used is about 10–20 nm and the length is from 1 to 2 µm. 250 mg MWCNT is added to the functionalizer solution so that it can be dissolved in water. The homogenous dispersion of MWCNTs is achieved after the mixed solution is sonicated for 60 minutes at 50 W. The solution is then centrifuged at 1000 rpm to remove large particles of undispersed MWCNTs to obtain a stable dispersed suspension. Later, PVA solution is prepared by dissolving 1 g of PVA (Mw = 89×10^3 g/mol) in 120 ml of deionized water. MWCNTs-PVA composite is concocted by adding the dispersed MWCNTs suspension into the PVA solution by one to four ratio. After sonificating the mixture for more than one hour, a homogeneous MWCNTs-PVA composite was obtained. The MWCNT-PVA composite is casted onto a glass petri dish and left to dry at room temperature for about 24 hours to produce a thin film with a thickness around 50 μm. Fig. 1 shows the Raman spectrum of the MWCNTs film when it is excited by a 532 nm laser. The Raman spectrum of pure PVA film is also included in the figure for comparison purpose.

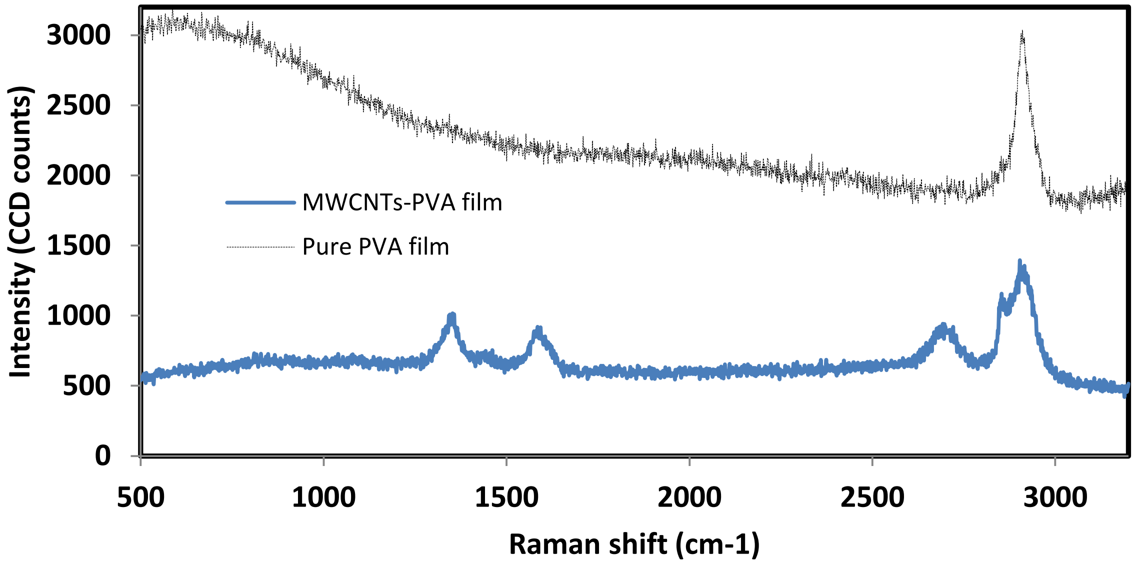

Fig. 1. Raman spectroscopy of pure PVA and MWNTs-PVA composites film.

As shown in Fig. 1, the Raman spectrum of the pure PVA film shows an intense peak at 2915 cm^{-1}. For the fabricated MWCNTs-PVA film, the Raman spectrum shows the G and D bands at 1593 cm^{-1} and 1356 cm^{-1}, respectively. The result is in good agreement to the values reported by Saito et. al. [9] and Kurti et al. [10]. The radial breathing mode (RBM), a distinctive feature of single-walled carbon nanotubes, is usually not observed in MWCNTs because the outer tubes restrict the breathing mode. The sample also produced a G' peak at 2720 cm^{-1} which originates from two-phonon scattering phenomena in the Brillouin zone. For MWCNTs-PVA polymer composite, another intense peak is also observed at 2915 cm^{-1} due to the introduction of host polymer.

3. Experimental setup

Fig. 2 shows the configuration of the proposed Q-switched YDFL using a MWCNT/PVA composite film as SA. The MWCNT/PVA SA is fabricated by cutting a small piece of the prepared film (2×2 mm^2) and sandwiching it between two FC/PC fiber connectors, after depositing index-matching gel onto the fiber ends. The insertion loss of the SA is measured to be around 2 dB at 1050 nm. The laser employs a 2 m long Ytterbium-doped fiber (YDF) with a core diameter of 4.0 µm, NA of 0.20 and cutoff wavelength of around 980 nm as the gain medium. The doping level of ytterbium ions in the fiber is 1500 ppm. The YDF is pumped by a 980 nm laser diode through a 980/1050 nm wavelength division multiplexer (WDM). An isolator is used in the ring cavity to ensure unidirectional propagation of oscillating laser. The output of the laser is tapped out of the cavity through a 3 dB coupler. The optical spectrum analyser (OSA) with a spectral resolution of 0.02 nm is used for the spectral analysis of the *Q*-switched YDFL whereas the 350MHz oscilloscope is used to observe the output pulse train of the *Q*-switched operation via a 460-kHz bandwidth photo-detector. The total cavity length of the ring resonator is around 12 m.

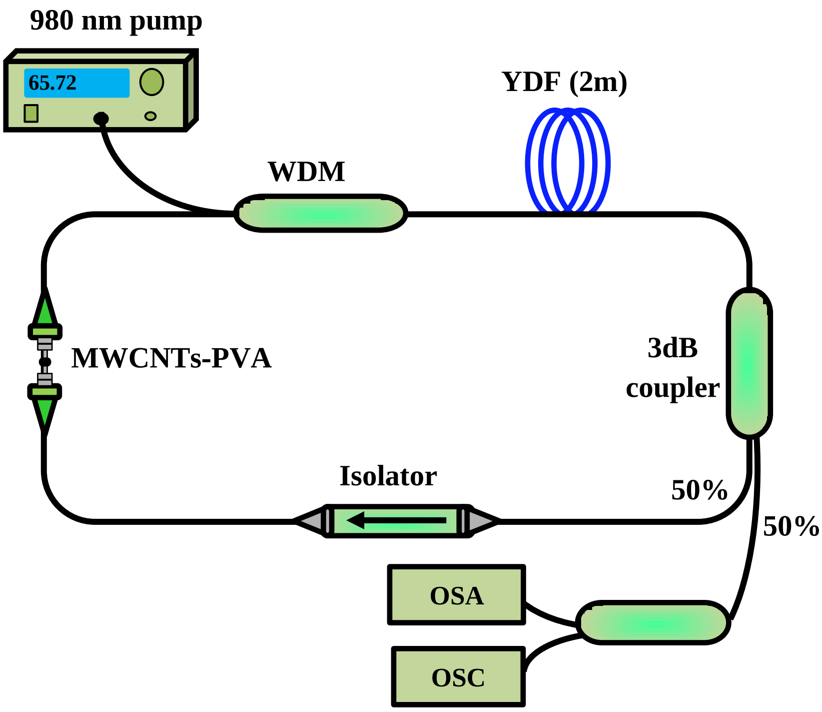

Fig. 2. Configuration of the proposed Q-switched YDFL utilizing a MWCNTs-PVA film based SA.

4. Results and discussion

The output spetrum of the passively Q-switched YDFL is investigated at various pump power and the result is shown in Fig. 3. From the figure, it can be seen that the laser operates at wavelength of 1058.6 nm as the pump power is increased above the threshold pump power of 65.72 mW. The peak power of the spectrum is observed to improve with the increase of pump power. The YDFL starts to generate a self-starting Q-switching pulse at threshold pump power of 65.72 mW. When the pump power is gradually increased from 65.72 to 97.29 mW, a stable pulse train with a varying repetition rate was observed. It is also observed that further increase of the pump power results in unstable pulsation. Figs. 4(a) and (b) shows the typical pulse train and it's single pulse envelop of the laser output respectively, at pump power of 97.29mW. The pulse shows the typical feature of passive Q-switching and no timing jitter is noticeable (limited by the sensitivity of 460-kHz detector). The pulse train has a period of 31.1 µs, which corresponds to a repetition rate of 32.19 kHz. The corresponding pulse envelop has the the symmetrical Gaussian-like shape with full-width at half-maximum (FWHM) of 6.677 µs.

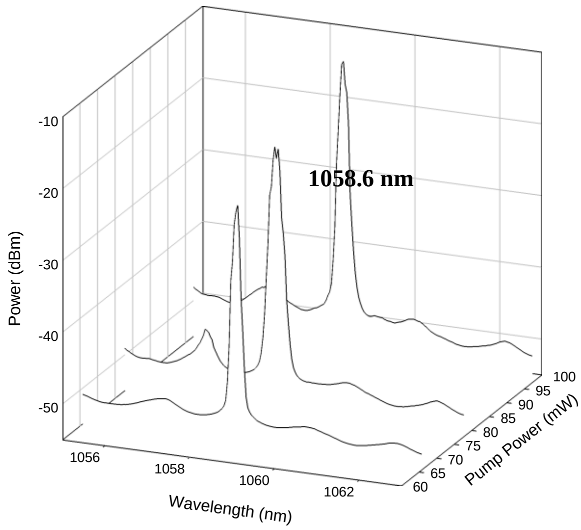

Fig. 3. Output spectra of the Q-switched YDFL at different pump powers.

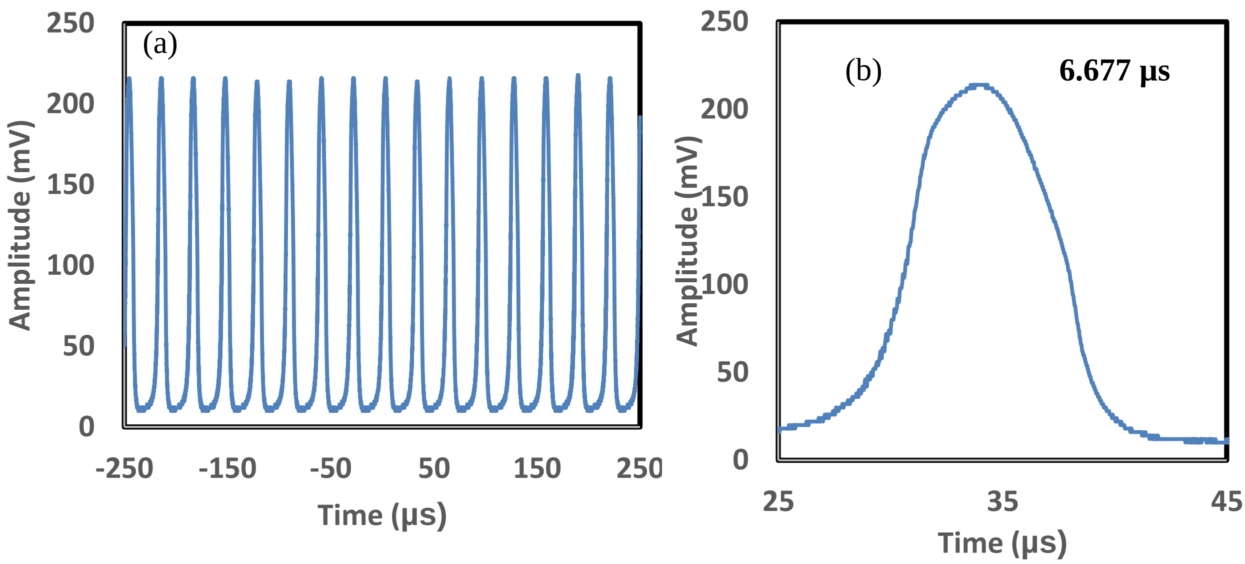

Fig. 4. Typical pulse train and single-pulse envelop of the Q-switched YDFL at pump power of 97.29 mW. (a) pulse train (b) pulse envelop.

Unlike passively mode-locking condition where the repetition rate of the output pulses is fixed corresponding to the cavity length [11], the repetition rate of a Q-switched fiber laser can be varied with reference to the lifetime of gain medium as well as pump power. Since different pump powers induce different time required to replenish the extracted energy between two consecutive pulses, the detuning of repetition rate occurs. Fig. 5 shows the repetition rate and average output power as a function of 980-nm pump power. It is found that both repetition rate and average output power monotonically increase with the pump power. The repetition rate is detuned from 5.48 to 32.19 kHz as the pump power increases from 65.72 to 97.29 mW, confirming the constructed laser is working under passive Q-switching. The output power increases from 1.05 mW to 5.64 mW as the pump power varies within the same range. This is attributed to the Ytterbium ions in the fiber, which are excited to a higher level even faster and the carbon nanotubes that are saturated faster as well which give a higher repetition rate.

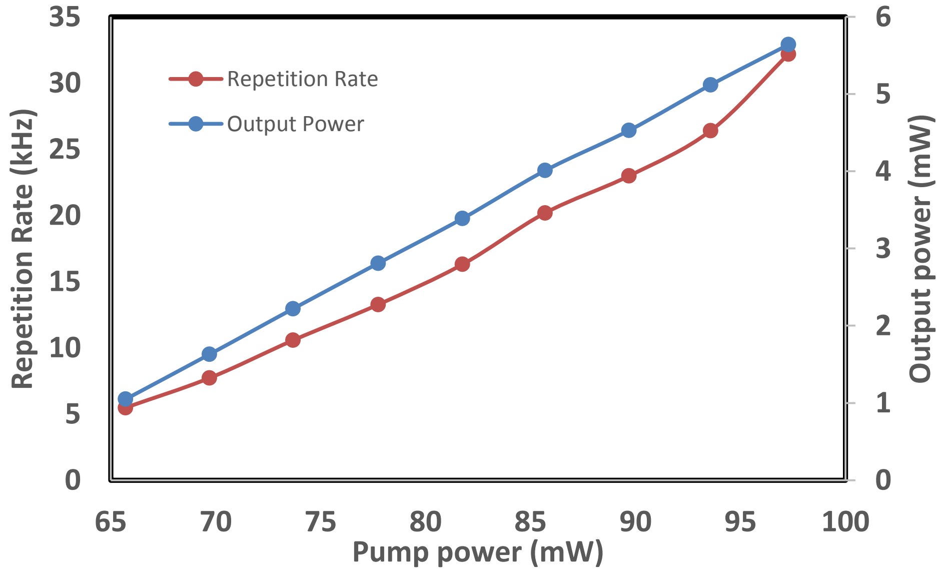

Fig. 5. Repetition rate and average output power for different pump powers.

Fig. 6 shows the pulse width and pulse energy of the Q-switched YDFL as a function of 980 nm pump power. As the pump power is increased from 65.72 mW to 69.71 mW, more gain is provided to saturate the SA, which in turn reduces the pulse width and increases the output pulse energy. However, the pulse energy fluctuates and then reduces with further increase in pump power. This is due to the pulse width of the output laser that exhibits increasing trend at this pump power region. As the pump power grows, the non-radiative decay rate of Yb^{3+} ions also increases. This generates heat in the laser cavity where the MWCNTs end up absorbing. This will energize some electrons in the MWCNT's valence band to move up to the conduction band from the strong internal thermal motion. As less electron in the valence band are available for photon absorption, the initial transmittance of the SA becomes greater as the pump power or absorbed heat increases. Thus MWCNT's efficiency as SA drops such that the pulse width begins to increase as the pump power reaches 69.71 mW as shown in Fig. 6. The pulse width increases from 4.2 to 6.7 μs as the pump power is increased from 69.71 to 97.29 mW. The maximum pulse energy of 211.8 nJ is obtained at the pump power of 77.75 mW. The pulse energy could be improved by reducing the insertion loss of the SA or by optimizing the laser cavity. The Q-switching can be maintained up to a pump power of 97.29 mW, where the energy is larger than previously reported SWCNT based Q-switched fiber lasers [12]. The pulse becomes unstable and disappears as the pump power is further increased.

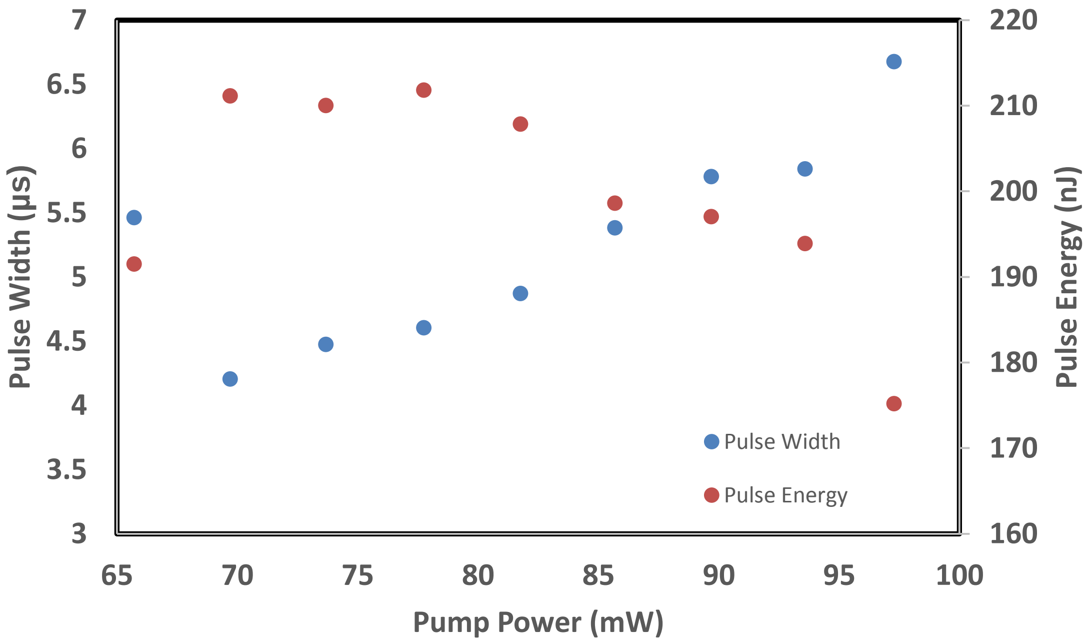

Fig. 6. Pulse width and pulse energy as a function of the pump power.

5. Conclusion

A passively Q-switched ring YDFL is demonstrated using MWCNTs embedded in PVA film as a saturable absorber. The SA film is prepared by mixing the MWCNTs homogeneous solution into a dilute PVA polymer solution. A small piece of the film is sandwiched between two FC/PC fiber connectors and integrated into the laser cavity to generate a stable Q-switching pulse operating at wavelength of 1058.6 nm within a pump power range of 65.72 to 97.29 mW. The repetition rate of the laser can be varied from 5.484 to 32.19 kHz by varying the pump power. The lowest pulse width of 4.2 μs is obtained at the pump power of 69.71 mW while the highest pulse energy of 211.8 nJ is obtained at pump power of 77.75 mW.

Acknowledgement

This work is financially supported by University of Malaya under various grant schemes (Grant No: RP008D-13AET and PG100-2014B) and Ministry of Science, Technology and Innovation (Grant No.: SF014-2014).

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