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Passively Q-switched erbium-doped fiber laser at L-band region by employing multi-walled carbon nanotubes as saturable absorber

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An inexpensive and simple passively Q-switched Erbium-doped fiber laser (EDFL) operating in the L-band region with a stable pulse train is generated by employing a multi-walled carbon nanotubes (MWCNTs) polymer composite film based saturable absorber. By incorporating the SA with a 50 m Erbium doped fiber (EDF) in a laser cavity, Q-switched pulse generation in the L-band region is made possible. The repetition rate of the pulse train ranges from 12.3 kHz to 14.4 kHz as the 1480 nm pump power is varied from 89.4 mW to 106.1 mW. At the highest pump power of 106.1 mW, the pulse width and pulse energy of the laser are 10.8 µs and 135.1 nJ, correspondingly. The saturable absorber (SA) is constructed from a tiny piece of MWCNTs thin film sandwiched between two FC/PC fiber connectors. The film is prepared by mixing MWCNTs homogeneous solution with a diluted Polyvinyl alcohol (PVA) polymer solution and left to dry at room temperature.

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1. Introduction

Passively Q-switched Erbium-doped fiber lasers (EDFLs) have been studied by many researchers for various applications such as in wavelength-division-multiplexed (WDM) transmission systems, fiber sensor, laser processing, laser marking and others [1-3]. Q-switched EDFLs operating in the long-wavelength band (L-band) region is particularly desired due to the inadequate channel capacity of the dense wavelength division multiplexed (DWDM) systems in C-band [4]. In addition, fiber loss is slightly lower in the L-band region in comparison to that of the C-band [5]. There are several types of saturable absorbers (SAs) that have been used to obtain Q-switching in EDFLs such as semiconductor saturable absorber mirrors (SESAMs) [6], transition metal-doped bulk crystals [7], and single-walled carbon nanotubes (SWCNT) [8-9]. The factors that restrict widespread use of SESAMs and transition metal doped bulk crystal SAs are their complicated, costly fabrication and limited compatibility with many optical fibers. On the other hand, recently introduced SWCNT SAs are simple to construct, cheap and have extensive fiber compatibility with wide operating bandwidth [10].

Multi-walled carbon nanotubes (MWCNTs) has drawn a lot of interests as it is simpler to produce and cheaper than SWCNTs [11-13]. Furthermore, MWCNTs shows a good thermal stability, which is very crucial in high power ultrafast laser development. Compared to SWCNTs, the MWCNTs offers higher mechanical strength and can absorb more photons per nanotube due to the higher mass density of the multi-walls. These features are believed to be associated with the configuration of MWCNTs which is in the form of stacked concentrically rolled graphene sheets where the outer walls can shield the inner walls from impairment or oxidation. This results in a higher thermal or laser damage threshold for the MWCNT than that of the SWCNTs [15].

So far, there are few reported works on the application of MWCNTs as SA to generate Q-switched EDFLs operating in the L-band region. In this paper, a Q-switched EDFL operating at 1566.36 nm is demonstrated using a MWCNTs-Polyvinyl alcohol (MWCNTs-PVA) based SA. The SA is fabricated by sandwiching the composite film between two fiber connectors.

2. Experiment

The experimental setup for the proposed laser is illustrated in Fig. 1. The 58 m long ring oscillator consists of an isolator, a wavelength-division multiplexer (WDM) coupler, a 50 m long erbium doped fiber (EDF), a MWCNT-PVA SA and an 95/5 output coupler. The isolator is used to ascertain unidirectional propagation of the oscillating laser in the cavity. We use a 1480 nm laser diode to pump the EDF through the 1480/1550 nm WDM. The EDF has a peak core absorption of 8.38 dB/m at 1530 nm, cut-off wavelength of 953 nm and numerical aperture of 0.24. The output of the laser is tapped from the cavity through a 95/5 coupler which keeps 95% of the light in the ring oscillator. The optical spectrum analyzer (OSA) is used to inspect the spectrum of the EDFL with a spectral resolution of 0.05 nm whereas the oscilloscope is used to observe the output pulse train via a 460 kHz bandwidth photo-detector (Thor lab, PDA50B-EC).

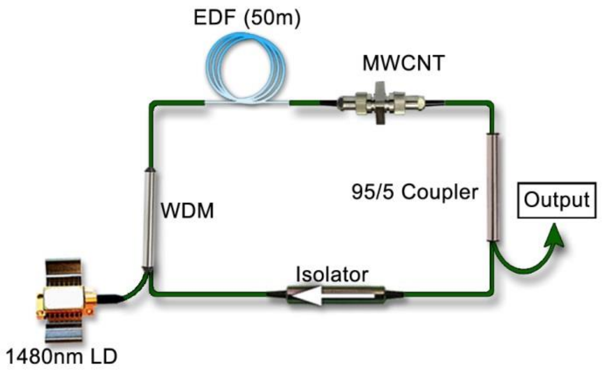

Fig. 1. Proposed configuration of the Q-switched EDFL.

A. *MWCNTs-based SA*

The MWCNTs possess a diameter of 10–20 nm with the length distribution of 1 to 2 µm. The first step in the fabrication process is to add 250 mg of the MWCNT powder into a solution, which was made from dissolving 4 g of sodium dodecyl sulphate (SDS) in 400 ml deionized water. The mixture is then sonicated for 60 minutes at 50 W before it is centrifuged at 1000 rpm to remove large particles of undispersed MWCNTs in order to obtain a homogeneously dispersed suspension. Then the dispersed MWCNTs suspension is poured into a PVA solution, made by dissolving 1 g of PVA (Mw = 89×103 g/mol) in 120 ml of deionized water, at the ratio of 3:2. Finally, the MWCNTs-PVA mixture is further sonificated for more than one hour to achieve homogeneous MWCNTs-PVA. A composite film with thickness of around 10 mm is acquired by spreading the composite solution onto a glass petri dish and left to dry at room temperature for about one week. Fig. 2(a) shows the MWCNT-PVA film after it already dries. We fabricated the SA by cutting a small part of the prepared MWCNT-PVA film at approximately 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 was measured to be around 3 dB at 1550 nm which is shown in Fig. 2(b) and 2(c).

We performed Raman spectroscopy on the MWCNTs-PVA film using laser excitation at 532 nm to confirm the presence of the carbon nanotubes. Fig. 3 shows the Raman spectrum which indicates the different features of the MWCNTs such as the G and G' bands at 1580 cm-1 and 2705 cm-1, respectively. The G band originates from in-plane tangential stretching of the carbon-carbon bonds in graphene sheet. The noticeable D band at approximately 1350 cm-1, is a hybridized vibrational mode associated with graphene edges and it indicates the presence of some disorder in the graphene structure. The Radial Breathing Mode (RBM) bands at the peaks of 200 and 300 cm^{-1} which resemble the expansion and contraction of the tubes, are not clearly present in the MWCNTs because the outer tubes restrict the breathing mode. The prominent D band suggests that the CNTs are of a multi-walled type of CNTs. The D' band is also observed at 1613 cm^{-1} as a result of double resonance feature induced by disorder and defect.

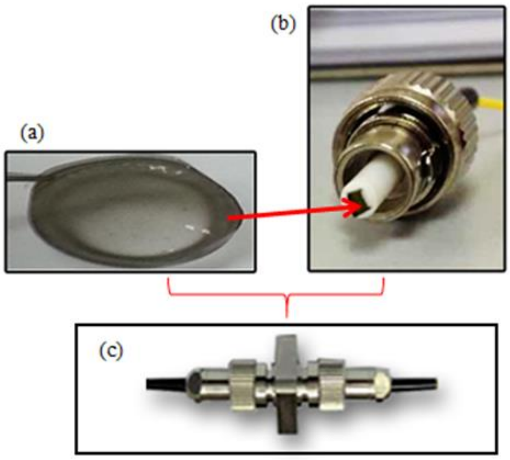

Fig. 2. (a) MWCNT-PVA PVA composite film with thickness of around 10 mm; (b) MWCNT-PVA film was cut into approximately the size of 2×2 mm^2 and placed on to the fiber ferrule after depositing index-matching gel onto the fiber ends; (c) SA is fabricated by sandwiching it between two FC/PC fiber connectors to be incorporated inside laser cavity.

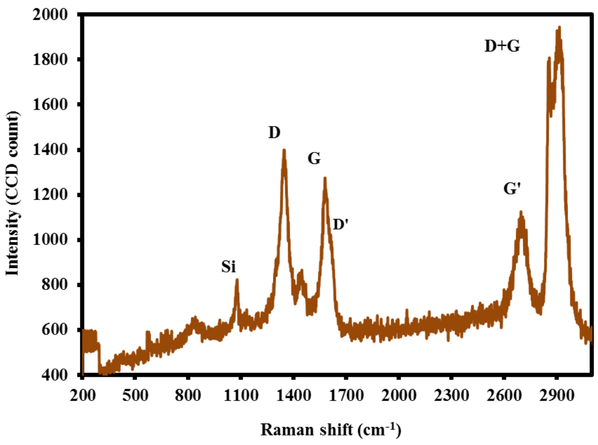

Fig. 3. Raman spectrum of the MWCNTs-PVA film.

3. Result and discussion

Stable and self-starting Q-switching operation is obtained with the pump power threshold of 89.4 mW. Fig.

4 displays the output spectrum of the EDFL with SA at the maximum pump power of 106.1 mW. We observed that the Q-switched laser operates at wavelength of 1566.34 nm which is in the L-band region. The peak power and OSNR of the Q-switched EDFL are degraded due to the increase in the total loss in the ring cavity.

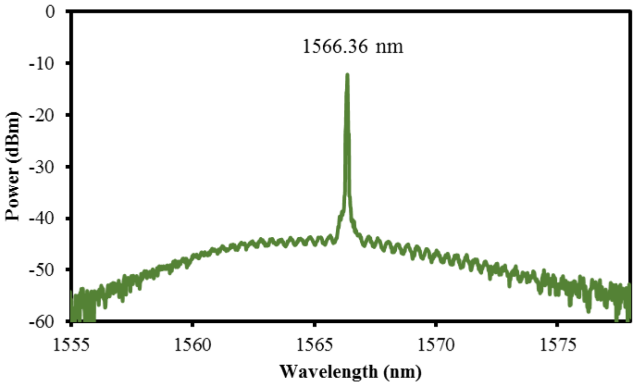

Fig. 4. Output spectrum of the proposed EDFL.

The oscilloscopes trace in Fig. 5 is portraying the typical Q-switched pulse train at pump power of 106.1 mW. The Q-switching operation is steady without distinct amplitude modulation observed in each Q-switched envelop of the spectrum. This proves that the self-mode locking effect on the Q-switching is strong. The repetition rate of 14.4 kHz is achieved in this pump power. Inset of Fig. 4 is a single pulse envelop of the Q-switched laser, which shows the pulse width of 10.8 µs at the same pump power.

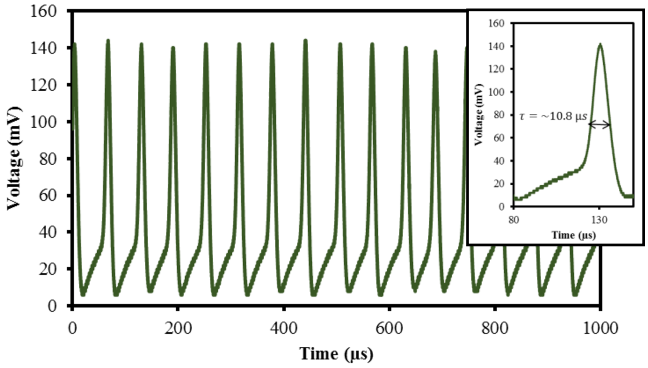

Fig. 5. A typical pulse train from the proposed EDFL at 106.1 mW. Inset is the single pulse envelop with pulse width of 10.8 µs.

Fig. 6 illustrates the repetition rate and pulse width relationships with the pump power. The graph portrays that the pulse repetition rate is increasing more or less linearly with the pump power, while the pulse width decreases in also almost linear fashion. This observation is consistent with the passive Q-switching theory when employing the SA [16]. The range of the pulse repetition rate of the L-band region Q-switched EDFL is between 12.3 kHz to 14.4 kHz with the pump power variation from 89.4 mW to 106.1 mW. Conversely, the pulse width decreases from 11.8 to 10.8 µs within the same pump power range. It is predicted that the pulse width will decrease more by increasing the pump power, provided that the damage threshold of the SA is not exceeded.

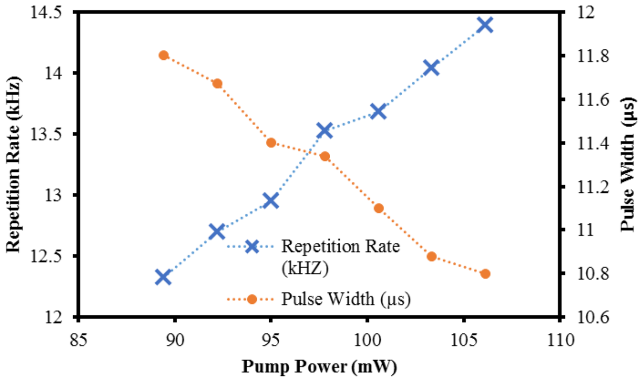

Fig. 6. Repetition rate and pulse width as a function of 980 nm pump power.

Fig. 7 indicates the relationship between pulse energy and peak power output of the proposed EDFL as functions of pump power. As observed, both pulse energy and peak power output increase with the rise in the pump power. The highest average power of 12 mW and the highest pulse energy of 135 nJ is achieved at the pump power of 106.1 mW. The pulse energy could become higher by increasing the pump power more. These results imply that MWCNTs employed as SA in the laser system has a bright prospect in producing superior Q-switching and saturable absorption with further research and development.

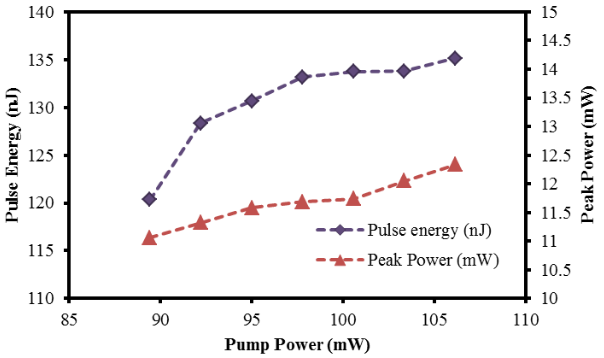

Fig. 7. Pulse energy and peak power as a function of 1480 nm pump power.

The fabrication of the MWCNT-PVA SA is also not complex and thus the cost of the laser should be cheaper. The simple and low cost laser may be suitable for applications in metrology, environmental sensing, biomedical diagnostics and L-band fiber optic communication.

4. Conclusion

A MWCNTs-PVA thin film based SA has successfully been deployed in a laser cavity to demonstrate a passive, stable and low cost Q-switched EDFL. The film was sandwiched between two ferrules to form the SA which was incorporated in the EDFL ring cavity to yield a Q-switched fiber laser operating in L-band region. The operating wavelength of the laser was 1566.34 nm. A stable pulse train with a repetition rate ranging from 12 kHz to 14.3 kHz was generated as the 1480 nm pump power was increased from 89.4 mW to 106.1 mW. At 106.1 mW pump power, the pulse width and pulse energy were 12 μs and 135 nJ, respectively. Other than demonstrating reliable Q-switching operation, the proposed SA is easy to fabricate and cheap thus making it an ideal component for generating Q-switched laser in the L-band.

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