Dual-wavelength passively Q-switched erbium-doped fiber laser with MWCNTs slurry as a saturable absorber

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Abstract—In this work, a compact, stable dual-wavelength Q-switched laser has been demonstrated, with a multi-walled carbon nanotubes (MWCNTs) slurry as a saturable absorber (SA) which is independent of any host polymer. The MWCNTs slurry is fabricated and the peak shift is investigated using Raman spectroscopy.The passively Q-switched erbium-doped fiber laser (EDFL) oscillated simultaneously at 1532.32nm and 1556.97nm with 24.67nm peak separation, at threshold and maximum input power of 26mW and 74mW, respectively. By increasing the input pump power from 36mW to 74mW, the pulse train repetition rate increases from 25kHz to 78kHz, while the pulse width is reduced from 17.84μs to 5.24μs. The generated pulse produced maximum pulse energy and maximum peak power of 11.97nJ and 2.05mW, respectively at maximum input pump power. The recorded signal to noise ratio is about 62dB and shows that the proposed MWCNTs slurry based SA is able to generate dual wavelength Q-switched pulse laser with a high stability pulse.

The generation of high energy laser pulses often utilizes Q-switching fiber lasers technology that brings about various applications in many industrial and scientific sectors including laser processing, medicine, telecommunications, range finding, metal cutting and remote sensing [1-2]. Actively Q-switched fiber lasers use optical modulation devices which made them more complicated as compared to the passively Q-switching techniques. The simplicity, compactness and flexibility [3] that Q-switched fiber lasers offer, have made them preferable in laser pulse generation. A passively Q-switched fiber laser has employed different kinds of saturable absorber as a means to find the one that would best complement the characteristics of lasers.

Semiconductor saturable absorber mirrors (SESAMs), single-walled carbon nanotubes (SWNTs) as well as graphene have been widely investigated in passively Q-switched EDFL. Though it is thought that the said SA is ideal with an all-fiber cavity configuration, many researches have been continuously conducted to find a better if not the best SA to surmount the drawbacks of the previous SAs. SESAMs fabrication is complex, intricate and expensive [2-3]. It also has a narrow operation waveband and limited range of optical responses. This resulted in restricted pulse generation [4-5]. SWNTs-based SAs though deemed to be simple and inexpensive fabrication-wise, have higher surface energy causing them to be less stable, lower damage threshold and lack reliability as well. Having a much lower saturation intensity and a higher damage threshold as compared to SWNTs, graphene is seen as a better SA as it can allow better saturable absorption as well as ultrafast recovery time [6]. However, graphene has relatively weak optical absorptions. Therefore, based on the drawbacks in the properties of the previous SAs, this research will demonstrate a compact and stable dual-wavelength Q-switched laser with MWCNTs slurries as a saturable absorber. As a family type of carbon nanotubes, MWCNTs promise lower fabrication cost as they do not need special techniques or treatment to be fabricated [7]. They possess a sturdy mechanical strength, as well as higher thermal stability and damage threshold as compared to SWCNTs. Having multiple walls has made them capable of absorbing more photons energy per nanotubes [8].

The generation of a dual wavelength Q-switched fiber laser is crucial as it brings about many advantages over single wavelength generation particularly as a medium in various applications such as supercontinuum generation, terahertz generation and nonlinear optics [9-10]. In a fiber laser, the generation of a passively dual wavelength laser was demonstrated by using a various range of materials as a saturable absorber, including selenium bismuth (Bi_2Se_3), graphene, tungsten disulphide (WS_2), molybdenum disulphide (MoS_2), black phosphorus (BP) as well as SWNTs, among many others [1-4,11-14]. For instance, passively Q-switched EDFL based on a SWNT/polymide polymer composite based saturable absorber was shown to oscillate simultaneously at 1532nm and 1558nm with 26nm peak separation within the range input pump power from 62mW to 120mW [1]. Graphene-based SA is also widely used in Q-switched dual wavelength pulse laser generation taking examples of the work by Luo *et al*. [2] and Wang *et al*. [13] which successfully demonstrated dual wavelength oscillation at 1566.17nm and 1566.35nm

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as well as 1531.12nm and 1556.79nm respectively. Recently, SA based on BP has been reported to generate dual wavelengths Q-switched in one micron cavity. The wavelengths peaks at 1038.68nm and 1042.05nm both emerging at pump power of 158.8mW [4]. MWCNTs-based SA is often used in obtaining a multi-wavelengths spectrum, one of which is reported by Tiu *et al.* which produces at least 14 lines with a spectral range of 0.48nm using MWCNTs-PVA composite [15].

One of the drawbacks of using MWCNTs polymer composites is that the performance of the SA is limited by the host polymer. Apart from that, the dispersion states of carbon nanotubes are the most crucial factor that determines the mechanical properties of carbon nanotubes polymer composites and the good dispersion of nanotubes is crucial for any composite. Thus, the search for MWCNT slurries independent of the host polymer as SA is still going on.

The MWCNTs slurry used in the study was fabricated by using MWCNTs in acrylonitrile-butadiene-styrene (ABS) based for 3D-printed filament as the starting material which is purchased online from 3Dxtech. The filament is 2.85mm and 750g in diameter and weight, respectively. Initially, the MWCNTs-ABS filament was extruded by using 3D printer with a nozzle diameter of 0.4mm at 210^{o}C to reduce its diameter to 200µm. The resulted filament weighing 25mg was then mixed with 1ml acetone before it was ultrasonic treated for 5 minutes to dissolve the ABS. As a result, MWCNTs-acetone suspension was produced. The morphology of the MWCNTs slurry was investigated using the Field-Emission Scanning Electron Microscope (FESEM) by drop casting the suspension on a glass slide where the acetone evaporated producing MWCNTs slurry. Figure 1 shows the image of the MWCNTs slurry with a discerning bundle of MWCNTs. The Raman spectroscopy of the SA was performed using LabRAM HR Evolution to investigate the peak shift. Figure 2 represents the raman shift of MWCNTs slurry with a D-band, G-band and G'-band at 1346cm^{-1}, 1574cm^{-1} and 2694cm^{-1}, respectively. The measured insertion loss is approximately around 4.5dB at 1550nm.

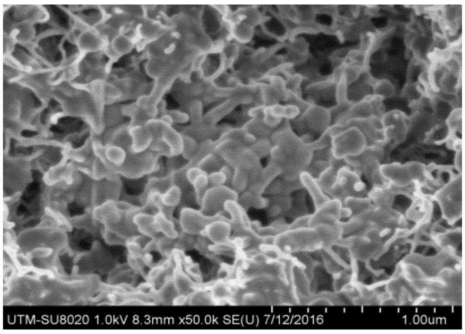

Fig. 1. Field-Emission Scanning Electron Microscope (FESEM) image of MWCNTs slurry.

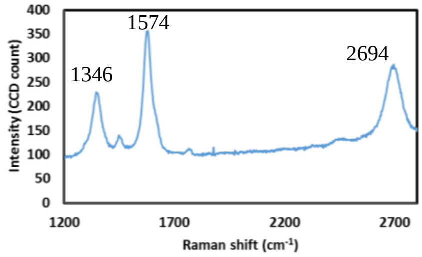

Fig. 2. Raman spectroscopy of MWCNTs slurry.

The experimental setup of the passively Q-switched EDFL is as shown in Fig. 3. A 1-m-long Erbium-doped fiber (EDF) was used as a gain medium. The setup also consists of a 1480/1550nm wavelength division multiplexer (WDM), isolator, newly fabricated MWCNTs slurry as SA, and a 95/5 output coupler, arranged in a ring configuration. The core and cladding diameter of the EDF is 8µm and 125µm respectively. The numerical aperture of the EDF is 0.16 and has Erbium ion absorptions of 45dB/m at 1480nm and 80dB/m at 1530nm. The EDF was pumped by a 980nm laser diode via the WDM. An isolator was incorporated in the laser cavity to ensure unidirectional propagation of the oscillating laser. The output of the laser was tapped from the cavity through a 95/5 coupler while keeping 95% of the light to oscillate in the ring cavity. The spectrum of the EDFL was inspected by using the optical spectrum analyzer (OSA) with a spectral resolution of 0.05nm, whereas an oscilloscope was used to observe the output pulse train via a 460kHz bandwidth photo-detector.

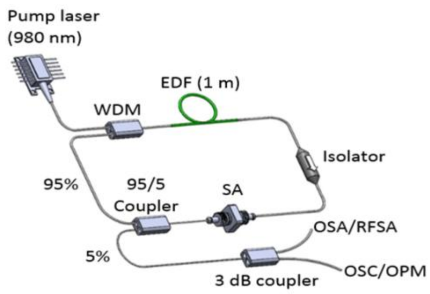

Fig. 3. Experimental setup of the proposed dual-wavelength passively Q-switched EDFL with MWCNTs slurries based SA.

The experimental research revealed that the passively Q-switched laser oscillated simultaneously at 1532.32nm and 1556.97nm with a 24.67nm peak separation with a threshold input pump power of 26mW and maximum input pump power of 74mW. The threshold pump power for dual wavelength passively Q-switched is lower than in the research reported in [1, 4, 11, 13] that uses SWNT, BP, Bi_2Se_3, and graphene- based SA. The OSA trace is shown in Fig. 4 showing the 3dB bandwidth at 1532.32nm is around 2.5nm, higher than the wavelength at 1556.97nm which is around 0.6nm, showing same phenomena as reported in [1].

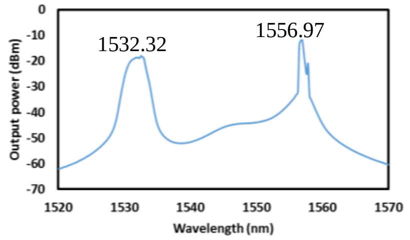

Fig. 4. OSA trace of Dual-wavelength pulsed fiber laser.

Figure 5 shows a typical pulse train and single pulse envelope at a maximum incident pump power of 74mW. The generated stable pulse train is 78kHz with a pulse width of 5.24µs.

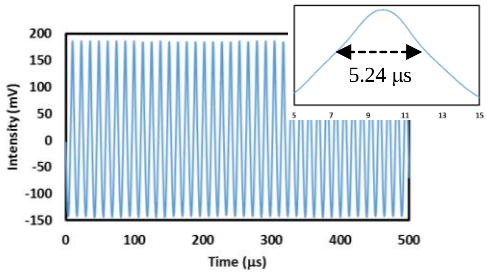

Fig. 5. Pulse train and single pulse envelope at 74mW.

Figure 6 illustrates the repetition and pulse width versus the input pump power. By increasing the input pump power from 26mW to 74mW, the pulse train repetition rate increases from 25kHz to 78kHz, while the pulse width is narrowed from 17.84µs to 5.24µs, making the obtained shortest pulse width better than the reported works in [8, 11, 15]. Figure 7 shows instantaneous peak power and pulse energy versus pump power. The generated pulse produced a maximum peak power and maximum pulse energy of 2.05mW and 11.97nJ, respectively, at maximum input pump power. Figures 6 and 7 show a typical trend of the Q-switched pulse laser as reported by other researchers [1-4, 11-14], with the advantage of dual wavelength generation.

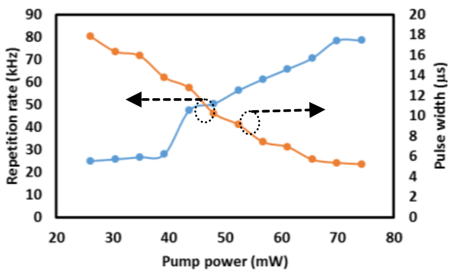

Fig. 6. Repetition rate and pulse width versus pump power.

The stability of the generated pulse was further investigated using a radio frequency spectrum analyzer (RFSA) to measure the signal-to-noise ratio (SNR). Figure 8 shows the recorded RFSA at maximum pump power with a 500kHz span. The first beat note at 78kHz is about 62dB indicating high pulse stability and the SNR higher than that the reported by using a 2D material [4, 9].

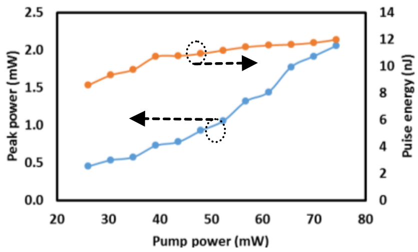

Fig. 7. Peak power and pulse energy versus pump power.

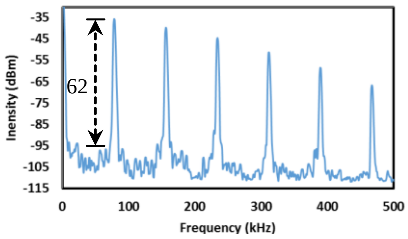

Fig. 8. RFSA measurement of SNR at 74mW.

In conclusion, the proposed application of the 3D MWCNT-ABS filament as a starting material to fabricate MWCNTs slurry based SA was successfully demonstrated. Four-wave mixing (FWM) was induced due to the strong third-order nonlinear optical property of the MWCNTs slurry. The self-stabilizing effect [2] from the FWM helps to overcome the mode competition in the EDF, which aided simultaneous dual wavelength generation.

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