Nanotube Mode-Locker with Tuneable Wavelength

Nur Hidayah Muhamad Apandi
Malaysia-Japan International Institute of Technology
Kuala Lumpur, Malaysia
nurhidayahapandi@gmail.com

Fauzan Ahmad
Malaysia-Japan International Institute of Technology (MJIIT)
Universiti Teknologi Malaysia,
Kuala Lumpur, Malaysia
fauzan.kl@utm.my

Harith Ahmad
Dept. of Physics
University of Malaya,
Kuala Lumpur, Malaysia
harith@um.edu.my

Siti Nur Fatin Zuikafly
Malaysia-Japan International Institute of Technology (MJIIT)
Universiti Teknologi Malaysia,
Kuala Lumpur, Malaysia
snfatin.02@gmail.com

Mohd Haniff Ibrahim
Faculty of Engineering
Universiti Teknologi Malaysia
Johor Bahru, Malaysia
hanif@fke.utm.my

***Abstract*— A wavelength-tunable passively Erbium-doped mode-locked fiber laser by residing single-walled carbon nanotubes (SWCNTs) embedded in polyethylene oxide (PEO) based saturable absorber (SA) is demonstrated.The mode-locker is fabricated by solution casting method of single-walled carbon nanotubes embedded in polyethylene oxide as host polymer. The fabricated nanotube based mode-locker is resided in Erbium doped fiber laser in ring cavity.In this experiment, tuning is performed using a tunable Mach-Zehnder filter (TMZF) for the tuning of output wavelength continuity of 20 nm (from 1544 nm to 1564 nm). The tunable pulse duration is range from 300 fs to 435 fs, maximum output power of 0.91 mW and signal to noise ratio (SNR) of 40 dB.**

Keywords—nanotube, soliton, tuneable wavelength

I. INTRODUCTION

Flexibility, high beam quality, and high power lasers are some of the advantages Q-switching laser operation can offer aside from being alignment free and having low cavity losses as less instrument is needed in the cavity. The previously raved fiber lasers' saturable absorbers (SAs) such as semiconductor saturable absorber mirror (SESAMs), and transition metal doped crystals [1,2] have been less attractive due to their complex and expensive fabrication process. Due to many limitations of past SAs, carbon nanotubes (CNTs) which depending on its crystalline structure can be single-walled carbon nanotubes (SWCNTs) or multi-walled carbon nanotubes (MWCNTs), has become one of the highly exploited material for SA fabrications. The tuneability of the CNTs' band gap as well as its broadband absorption spectrum has made it widely popular among researchers. As the name denotes, SWCNTs consists of a single layered graphene sheets which is rolled into a cylinder acting as a 1 dimensional structure. With SWCNTs specifically, the advantage of having sub-picosecond recovery time [3], low saturation intensity, as well as mechanically robust has brought about many potential applications as good SA [4]. In Q-switched fiber lasers achieved through passive technique, SWCNTs have been demonstrated, again and again, to exhibit excellent optical properties in generating pulsed fiber lasers since its first demonstration by Set et al. in 2004 [4] [5-7]. Meanwhile, in achieving lasers' mode-locking using SAs such as SWCNTs, many techniques has been discussed such as through evanescent field interaction in tapered fiber, as well as D-shaped fiber [8,9] and in broad wavelength regions i.e 1 μm, 1.5 μm, and 2 μm [3][10,11].

Usually, the integration of the SWCNTs as SA was made easier by incorporating it with some type of polymer to form a thin film composite which made it easier to be attached and removed from the laser cavity. Liu et al. [12] demonstrated a SWCNTs-polyimide (PI) based SA to yield a passively Q-switched fiber laser, producing a shortest pulse width of approximately 6 μs. In 2 μm region using Thulium-doped fiber as the gain medium, a work by Wang et al [13] reported a 152 fs laser using SWCNTs grown by arc discharge on Ni/Y catalyst. In 2013, Ahmad et al., [14] successfully reported a tuneable mode-locked laser based on graphene through aid of tuneable Mach-Zehnder filter (TMZF). The attained soliton mode-locking of the central wavelength was tuneable from 1551 nm to 1570 nm which was about 19 nm in wavelength range. Recently, Li et al., [15] demonstrated a wavelength tuneable laser through mode-locking using SWCNTs based SA with sodium-carboxymethycellulose (Na-CMC) as host polymer. The wavelength tuneability is made possible with the incorporation of a tuneable bandpass and wavelength filter (TBWF). The laser's output wavelength was tuneable over 34 nm bandwidth with pulse duration variation from 545 fs to 6.1 ps allowing for various research applications.

II. METHODOLOGY

A. Fabrication and Characterization of SWCNTs-PEO

SWCNTs-PEO is fabricated in a way that have been proposed by Ahmad [16]. The fabricated SA was studied through Raman spectroscopy to attest to the unique chemical composition of the SWCNT itself within the SA composite. Fig. 1 shows the Raman study of SWCNTs-PEO SA composite. At 1586 cm^{-1}, a distinct peak called G band can be observed. This originated from tangential vibrations of the

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carbon atoms [17]. The G- band diverged into another peak at 1533 cm-1 due to C-C stretching mode, due to the curvature instigated variation of the rearranged bonds directions [18]. The D-band phonon was located at 1315 cm^{-1} and the G'-band was at 2633 cm^{-1}. Both peaks were located within the range of significant peaks of SWCNTs. The distinct peak of radial breathing mode (RBM) was observed at 268 cm^{-1} and the diameter of SWCNTs-PEO was estimated to be 0.93 nm.

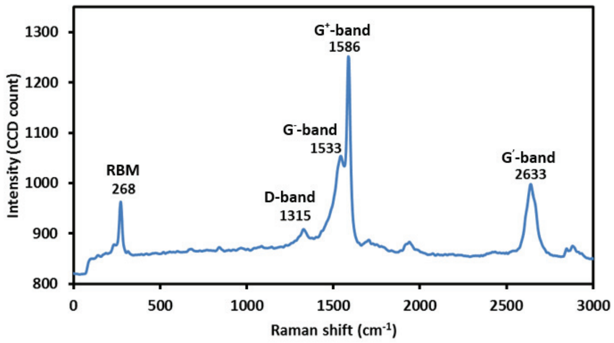

Fig. 1. Raman spectrum of the SWCNTs-PEO composite film with distinct peaks of G-band, D-band, G'-band and RBM.

The representational of the fiber laser's setup is depicted in Fig. 2. A 3m Erbium doped fiber (EDF) (IsoGain I-25(980/125), with cut-off wavelength of 900 nm to 970 nm, numerical aperture (NA) of 0.23-0.26, and absorption of 35-45 at 1550 nm was used as the gain medium. A 974 nm laser was pumped from LD through a 980/1550 nm wavelength division multiplexer (WDM).

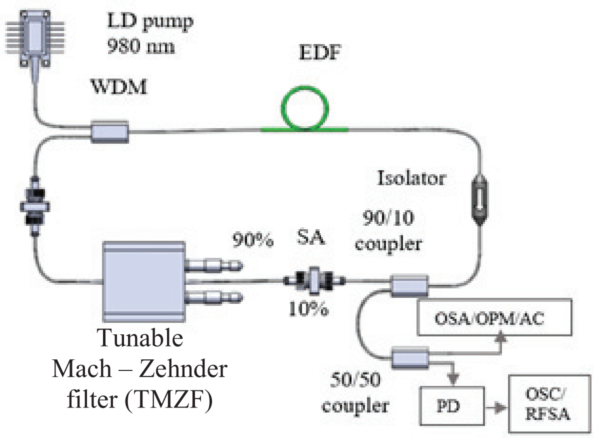

Fig. 2. Experimental Setup.

The SWCNTs-PEO SA was sandwiched in between two fiber ferrule and a 90/10 fiber coupler was spliced into the cavity. 10% of the output was halved using a 50/50 coupler to record the concurrent output measurements through a 500-MHz oscilloscope (Yokogawa DLM2054 with a 1.2 GHz photo-detector), a radio frequency spectrum analyzer (RFSA), optical power meter (OPM) and an optical spectrum analyzer (OSA) (Yokogawa AQ6307C). To make certain of the light's undeviating route, an optical isolator was placed after the optical coupler. A tuneable Mach-Zehnder filter acted as an additional component to allow for the observation of the mode-locked laser's tuneability in terms of wavelengths and pulse durations.

III. RESULTS AND DISCUSSIONS

Firstly, the fiber laser's performance in mode-locking regime was identified before the integration of the tuneable Mach–Zehnder filter. The CW laser output was achieved at the pump power of 50 mW. At 65 mW, the self-started mode-locked pulse was observed as the continuous wave laser was transformed to costant mode-locked pulses with an output power of 0.77 mW as shown in Fig. 3. This revealed a typical case of conventional solitons centered at 1560 nm. The two sidebands were located at 1542.94 nm and 1576.16 nm with a 3-dB spectral bandwidth of 15.7 nm. The significant value of the 3-dB bandwidth is due to spectral broadening induced by the non-linear optical properties of single-walled carbon nanotubes. Fig. 4 shows the pulse duration, plotted against its $sech^2$ temporal profile by using HAC 200 auto correlator (Alnair). The measured pulse duration was at 600 fs. From the pulse duration of the soliton-like pulse, the time bandwidth product (TBP) was calculated at 0.67, slightly higher than that of a normal $sech^2$ transform-limited pulse of 0.315. The high value of TBP is due to the high value of 3-dB spectral bandwidth and indicating the chirping of the generated pulses. Fig. 5 depicts the typical mode-locked pulse train which show a low amplitude modulation with the repetition rate of 23.8 MHz corresponding to pulse interval of 42 ns. The measured repetition rate is also corresponding to the experimental setup length of around 9 meter. As described in Fig. 6, radio spectrum analyser measurement indicating a peak of signal to noise ratio (SNR) of ~60 dB indicating that the laser was operating with high stability.

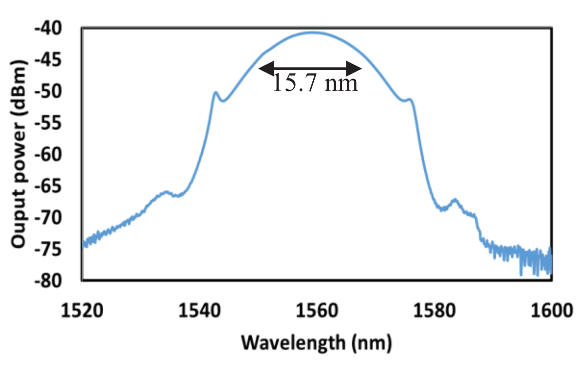

Fig. 3. Optical spectrum of SWCNTs-PEO.

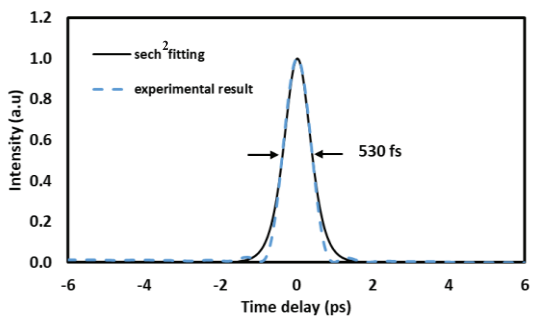

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Fig. 4. Autocorrelator trace of the conventional soliton at 1560 nm and input pump power of 11.67 mW.

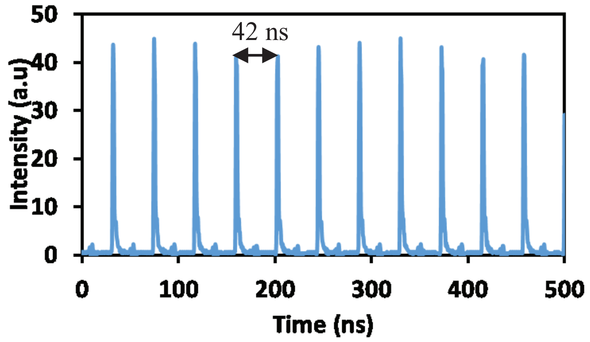

Fig. 5. Pulse train at 23.8 MHz.

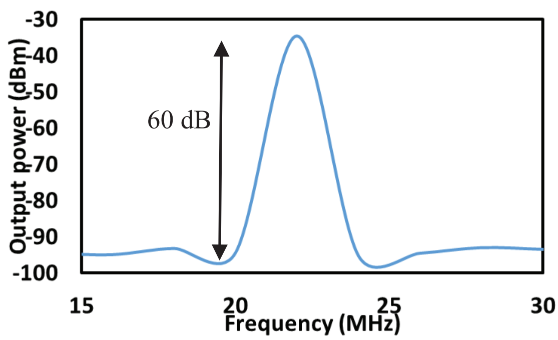

Fig. 6. RFSA measurement trace.

After characterizing the fundamental model-locked fiber laser, then, the wavelength tuneability of the mode-locked laser was measured by inserting a tuneable Mach – Zehnder filter (TMZF) at a fixed input pump power of 65 mW. Fig. 7 shows the tuneability range of the output wavelength within the span of 20 nm, from 1544 nm to 1564 nm. By inserting the TMZF in the laser cavity, the repetition was decreased to 13.88 MHz from 23.8 MHz, corresponding to the TMZF length of 6 m, while also agreeing to the total cavity length of around 15 m. The pulse duration at each of the central wavelength of the tunable wavelength was recorded as shown in Fig. 8. The pulse duration was observed to be tuneable from 300 fs to 435 fs where the shortest pulse duration was obtained at 1548 nm.

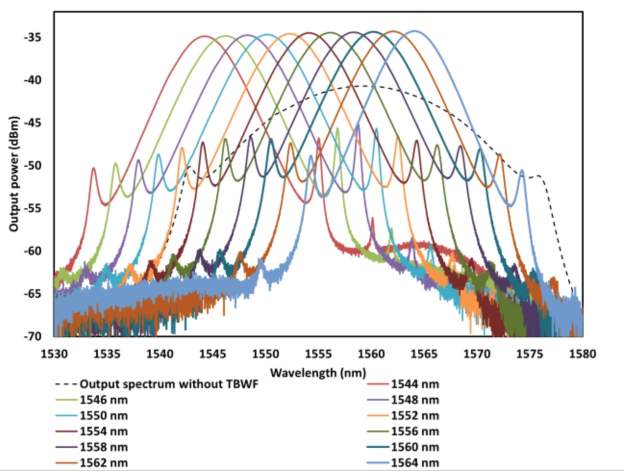

Fig. 7. Tunable wavelength with tunable Mach-Zehnder filter

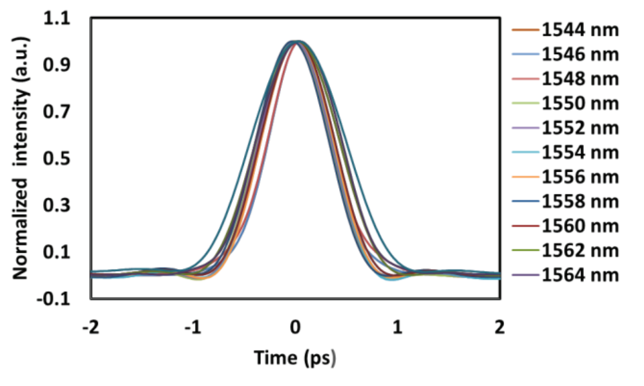

Fig. 8. Autocorrelator trace for tuneable wavelength.

The 3 dB bandwidth and the output powers recorded within the range of tuneability is as shown in Fig. 9. The 3 dB bandwidth and the corresponding average output power ranges from 2.2 nm to 8 nm and 0.77 mW to 0.91 mW, respectively. The maximum output power recorded was 0.91 mW with the shortest spectral width of 2.2 nm at 1552 nm. From the recorded value of 3 dB bandwidth and pulse width, the calculated time bandwidth product (TBP) for tuneable wavelength is fluctuated from 0.322 to 0.491, closer to the $sech^2$ transform limited pulse of TBP 0.315. By inserting the TMZF in the laser cavity, the recorded signal to noise ratio was decreased to 40 dB and indicated in Fig. 10.

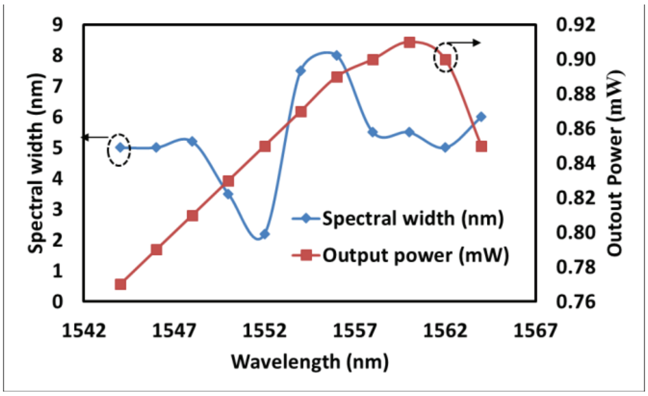

Fig. 9. 3 dB bandwidths and average output powers against central wavelengths.

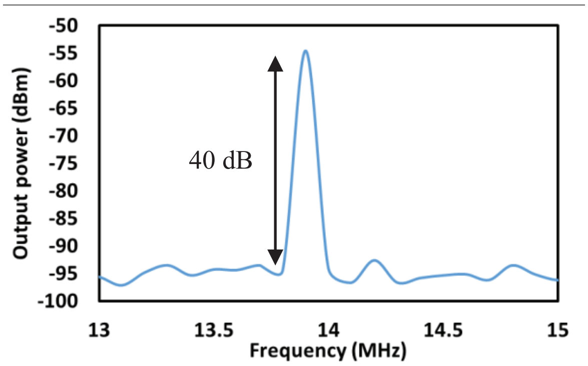

Fig. 10. Signal to noise ratio along the tunable wavelength.

IV. CONCLUSION

A passively mode-locked fiber laser with tuneable wavelength and pulse duration by using SWCNTs-PEO as SA was reported in this work. The conventional solitons were produced with sidebands at central wavelength of 1560 nm. The output wavelength can be continuously tuned within 20 nm wavelength range, from 1544 nm to 1564 nm with a wide pulse duration variation from 300 fs to 435 fs. Both ability to modulate the wavelength and pulse duration of the fiber laser reported in this paper can be utilized not only in basic researches, but also in commercial applications including optical signal processing, spectroscopy and telecommunication systems based on optic fibers.

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