68 MHz Fundamental Repetition Rates for Mode-Locked Erbium Doped Fiber Laser based Carbon Nanotube Saturable Absorber

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Abstract. A carbon nanotube thin film as saturable absorber in a cavity design of mode-locked fiber laser is reported in this work. Measured by power dependent absorption setup, 22% modulation depth of the saturable absorber is estimated which is ideal for stabilizing the mode-locked operation. Based on the scanning image from atomic force microscope (AFM), Single wall carbon nanotube components are identified existed in the thin film. The laser cavity employed a ~40 cm long erbium doped fiber as a gain medium which corresponds to the laser wavelength of 1550 nm (telecommunication wavelength region). Total length cavity of the fiber laser is about 3.1 m where shorter cavity design is required for higher repetition rate. This proposed system result in a firm soliton spectrum at centre wavelength of ~1561 nm with ~0.7 mW average output power and pulse duration of 410 fs. The pulses are generated at fundamental repetition rate of 68 MHz without any distortion and excellent spectral quality.

1. Introduction
Laser technologies had been improvised, and more advanced over decades of years as there is growth of demand for laser applications in certain fields. Many techniques had been developed and demonstrated to achieve better laser performance. One of the techniques is passively mode-locked laser, where it had extensively explored and reported due to its potential applications for ultrashort optical pulses generation in picosecond and femtosecond region [1–3]. Numerous application in fundamental research areas that involved short pulsed laser systems including medical and industrial fields are; time resolved studies in chemistry [4], optical frequency metrology [5], terahertz generation [6], and optical coherence tomosgraphy [7].

A saturable absorber introduced in the laser cavity can caused the laser to change its operation from continuous mode into a pulsed mode. The pulse often initiated by intensity dependent of nonlinear optical elements that response to support optical pulsation over continuous wave lasing. Also the proposing of fiber technologies had upgraded the technology in laser where difficulty and sensitivity of the solid state laser alignments can be reduced. Erbium doped fiber is mostly utilized as a gain medium as it is low cost and enables laser generation in communication wavelength of 1550 nm.
Particularly, the applications of carbon nanotubes (CNTs) as nonlinear saturable absorbers (SA) for passively mode-locked fiber lasers [8–11] is extremely attractive due to its optical performance, at once acquaint with new nanomaterials of wonderful physical and optical characteristic which triggered the study of new 2-D materials as well. CNTs ultrafast response time is influenced by packs of semiconducting and metallic CNTs that entangled together. The photons cause the electrons to excite in semiconducting CNTs couple to metallic CNTs, thus resulting in ultrafast recovery time of semiconducting CNTs shorter than 1 ps. This is one of the advantages of the CNTs. Other than ultrafast recovery time, the CNTs are advantage as it has wide absorption band [12]. In order to generate ultrashort pulses in femtosecond regime, a wide saturable absorption band is required to be inserted in the passively mode-locked laser cavity.

In this paper, we present the dynamics of a mode-locked Erbium fiber laser, which employs a CNT thin film as the mode-locking element. The laser produces ∼410 fs pulse duration but at repetition rate of ~68 MHz. Detailed spectral is recorded at different pumping levels and the operation of the laser is linked to the characteristics of the CNTs saturable absorber.

2. Experimental Method

2.1 CNT-SA Preparation and Optical Characterization

The carbon nanotube thin film in shape of polyvinyl alcohol (PVA) composite is merged onto the fiber ferule and sandwiched with another fiber ferule (connector) as in figure 1. The index matching gel is used to adhere the film onto the fiber ferule as well as to match the index of the ferule and the thin film. A topography image of carbon nanotubes is then obtained from a scanning probe microscope (SPM), SmartSPM™-1000 (AIST-NT). The semi-contact atomic force microscopy (AFM) technique was selected since this technique shown a quite obvious advantage against the contact AFM if any poorly fixed nanometer sized objects like carbon nanotubes was measured by AFM. Afterward, Raman spectroscopy with laser excited at wavelength 532 nm (2.33 eV) is conducted to show the difference between energy of absorbed and reemitted photons which indicates the energy needed to excite a molecule to a higher vibrational energy band.

![Figure 1](image_url). Assemble of saturable absorber by sandwiched CNT thin film with two fiber FC/PC connector.

2.2 Mode-Locked of Fiber Laser Setup

Setup of passively mode-locked erbium doped fiber laser is constructed in ring shape as depicted in figure 2. A 40 cm length of highly doped erbium fiber with absorption of 80 dB/m at wavelength of 1540 nm is pumped by a 980 nm laser diode through a wavelength division multiplexing (WDM) coupler. A polarization-independent isolator is employed in the cavity to ensure the unidirectional of the ring cavity as well as to help prevent the back-reflection in the cavity. Via a fiber output coupler, 90% of the light emissions are allowed to pass the CNT-SA and feedback into the ring cavity while 10% of the intra-cavity optical power is tapped as the output of the generated mode-locked laser. In this cavity, no polarization controller is acquired to match the round-trip polarization state in the fiber...
ring cavity as the light state polarization in the cavity is good enough to produce stable short pulse laser. The total cavity length of the fiber laser is measured at around 3.1 m. The 40 cm EDF has a dispersion of 12.6 ps$^2$ km$^{-1}$ at 1550 nm while the remain cavity has 2.5 m single mode fiber (SMF) with an anomalous dispersion of -22.8 ps$^2$ km$^{-1}$ and the 1 m HI-1060 fiber with dispersion of 6.75 ps$^2$ km$^{-1}$. Thus, the net cavity dispersion gives a negative value of -0.016 ps$^2$. The output is divided by 3 dB splitter, in order to simultaneously observe the pulse train and optical spectrum, where they are connected to the optical spectrum analyser (OSA) and oscilloscope through photodetector respectively. A radio frequency spectrum analyser (RFSA) with photodetector is employed to characterize the pulse train in frequency mode while the pulse width of the output laser is captured by an auto correlator.

3. Results And Discussions

Figure 3a) shows the CNT-SA properties of the nonlinear absorption measurement where the plotted graph resulting in ~22% of modulation depth, ~0.003 MW/cm$^2$ of saturation intensity, and 73 % of non-saturable absorbance that correspond to the peak intensity of 0.15 MW/cm$^2$. The modulation depth of the CNT in this work is slightly higher with difference around 5-8% compared to other works [13,14]. A better mode-locked fiber laser operation can be achieved if modulation depth normally more than 10 % is obtained [15]. Thus, this saturable absorber is suitable in generating better pulse shape laser. Additionally, high modulation depth indicates that the saturable absorber is quite thick [16] and the relatively large value of the non-saturable absorbance of the CNT is due to the film thickness which contributed to the fiber-to-fiber spacing [13,14]. However, this high non-saturable absorbance (non-saturable losses) specifies high power losses thus minimize the efficiency of the laser output power. Raman spectrometer of the CNT thin film is shown in Figure 3b). The spectrum shows peaks of D and G-bands at wavelength shift $1464 \text{ cm}^{-1}$ and $1598 \text{ cm}^{-1}$ respectively. The silicon (Si) peaks is observed at $481 \text{ cm}^{-1}$ while the radial breathing mode (RBM) is at $187 \text{ cm}^{-1}$. Another peak that essential and showed the existence of CNTs is known as Tangential mode or G mode (from graphite) which is observed around $1598 \text{ cm}^{-1}$ in this CNTs thin film, up to six Raman peak are observed which prove that the CNTs is a single-walled carbon nanotubes (SWCNTs) that give rise to a multi-peak features [17]. Besides G-band, there is low peak intensity of disorder-induced D-band that represents
the resonance condition of the material. Commonly, 50% of Raman spectra from SWNTs exhibit observable D-band signals with low intensity. SWCNTs is in good resonance if strong signal with low signal to noise ratio (practically no D-band) is showed while large D-band peak intensity compared to the G-band peak in SWCNTs indicates the amorphous carbon presences thus showed the spectra is in bad resonance conditions with high signal to noise ratio. In this work, the peak is observed at ~1464 cm\(^{-1}\) which near to the D-band peak (~1450 cm\(^{-1}\)) obtained in [17]. It has very low intensity similar to other SWCNTs features observed between the RBM and G-bands peaks. Consequently, this verified that the saturable absorber employed is SWCNTs thin film. Figure 3c) is the AFM topography image resulted from the SmartSPM\textsuperscript{TM}-1000 (AIST-NT) scanning probe microscope. The scan area showed that the CNT is observed spiking out from the surface and dispersed in-homogenously into non-uniform Island like structure while the smooth background is the uniform thin film. This in-homogenous dispersion of the CNT has also been obtained in other research works include [18,19]. Thus, this confirmed the CNT existence in the thin film. Additionally, this CNT is categorized as single walled carbon nanotubes (SWNT) due to the tabulated spiking CNT on the thin film are lower and less dense compare to the multi-walled carbon nanotubes (MWNT) [20].

\begin{figure} 
\centering 
\includegraphics[width=\textwidth]{figure3.png} 
\caption{Optical characterization of the CNT-SA. a) nonlinear optical absorption measurement of CNT thin film, b) The Raman spectrum of CNT thin film, c) AFM topography images of CNT thin film} 
\end{figure}
In order to achieve high fundamental repetition rate, the gain medium of highly absorbance erbium doped fiber with 40 cm length is employed. This is one of the methods used to manage the cavity dispersion of the fiber laser and decrease the total cavity length. The characterizations of the mode-locked fiber laser outputs are observed commonly for its spectrum profile, pulse train repetition rate and frequency, also the laser pulse width. The results are illustrated in figure 4, where figure 4a) is the stable mode-locked spectrum profile obtained when the pump power applied at 63.5 mW and the average power of the mode-locked laser is measured at around 0.7 mW. The mode-locking fiber laser threshold is obtained at pump power of 52.6 mW. Similar to other works on CNTs thin film mode-locked fiber laser [13,18,21], this threshold power of the mode-locking fiber laser spectrum is in reasonably low power. Given that, only low input power is required to generate mode-locked laser spectrum in this fiber laser cavity. Also from figure 4a), the 3 dB bandwidth spectrum obtained is 10.54 nm at central wavelength of 1561 nm where the spectrum profile shows low intensity of Kelly sidebands. The sideband or known as chirped soliton is relatively large in the normal group velocity dispersions (GVD), thus we can assumed that this cavity is in anomalous dispersion regime which lead to less perturbation (chirp/Kelly sideband) to be occurred [22]. This cavity regime is also equivalent to the calculated cavity dispersion. Figure 4b) shows the autocorrelation trace of the full-width half-maximum (FWHM) of the pulse width which is 0.41 ps with fitted curve by sech² function. The time bandwidth product (TBP) of the laser is calculated to be 0.477, and the value near to the transform limited sech² pulse minor deviation of about 0.162. Then, corresponding to the fiber laser fundamental repetition rate of ~68 MHz, the total length of the laser cavity is calculated and estimated to be 3.1 m which is slightly difference from the measured cavity length (3.9 m). The pulse interval of the mode-locked fiber laser is measured by an oscilloscope at value of 15.4 ns as shows in figure 4c). Afterward, in the figure 4d) depicted the radio frequency (RF) spectrum profile for the generated pulses train in span of 120 MHz and 1.4 GHz (inset) with radio bandwidth (RBW) of 10 kHz. A ~68 MHz RF signal is observed at 49.5 dB with the suppressed background noise from the main peak. The wide span RF spectrum verifies stable operation of the mode locking without any Q-switching instability (inset of figure. 4d).
Figure 4. Mode-locking erbium doped fiber laser based on CNT-SA performance with 45 cm length of erbium doped fiber as gain medium. a) Optical spectra of the generated dissipative solitons at threshold power ~63.5 mW, b) the oscilloscope tracings for repetition rate ~65 MHz (c) the pulse width profile from auto correlator; (d) the radiofrequency spectral profile and insert: the wideband RF spectrum.

The mode-locked fiber laser is varied by the input pump powers, and the maximum pump power limited by laser pump source is 75.3 mW. Figure 5 shows the plotted of average power of fiber laser against the pump power source. Hence, the maximum average output power of the mode-locked fiber laser is 1.28 mW. The pulse energy and peak power obtained are considered to be at 0.019 nJ and 48.1 W respectively. This average power has low efficiency of 1.9 % but no power dropdown is obtained and we can assume that CNT-SA thin film can withstand strong laser illumination up to ~200 mW. The damage to the CNT-SA can be mitigated in the cavity as the gain medium of erbium doped fiber with highly absorbance is employed, thus reducing the light-matter interaction while propagating through the CNT-SA. Therefore, this cavity design provides an effective approach to the optical damage problem on the CNT-SA thin film. It also shortens the total length cavity needed and high fundamental repetition rate of the mode-locked laser can be achieved.

Figure 5. Average power of fiber laser against the pump power source
To the best of our knowledge, this is the first observation of Er-doped fiber laser using sandwiched CNT-SA thin film that can achieved fundamental repetition rate up to ~68 MHz without any distortion compared to the previous study [8,23–25]. Mostly, the study of mode-locked fiber laser are focused from the techniques in fabrication of the CNT-SA to the variation of saturable absorber material in order to enhanced the characterization of the mode-locked laser [26–28]. However in our study, we demonstrated the simple technique of CNT-SA and cavity shortened of the fiber laser which gives good advantage in term of low cost, effective and compact devices.

4. Conclusion
In summary, we demonstrated passively mode-locked erbium-doped fiber operation at the anomalous dispersion regime of fiber lasers based on a CNT-SA thin film through sandwiched interaction technique. The nonlinear optical properties demonstrated the possibility of CNT-SA as a saturable absorber in a passive mode-locked fiber laser. A fiber ring cavity of high absorption of erbium doped fiber is constructed as a gain medium to achieve high repetition rate. Successively, a stable and robust mode-locked pulse is generated with a spectral bandwidth of 10.54 nm at 1561 nm, 410 fs pulse duration, and ~68 MHz repetition rate.

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6. References
[1] Tang D Y 2001 Observation of bound states of solitons in a passively mode-locked fiber laser 64 2–4
[2] Grelu P, Chouli S, Soto-Crespo J M, Chang W, Ankiewicz A and Akhmediev N 2010 Dissipative solitons for mode-locked fiber lasers 2010 Photonics Glob. Conf. PGC 2010 6
[3] Li H P, Jing Z, Xia H D, Liao J K, Tang X G, Lu R G and Liu Y Z 2010 Different types of sideband generation in a passively mode-locked soliton fiber laser Proc. of SPIE; High-Power Lasers and Applications V vol 7843, ed R F W Upendra N. Singh, Dianyuan Fan, Jianquan Yao (SPIE) pp 784328–784328 – 7
[4] Burdzinski G and Platz M S 2010 Ultrafast time-resolved studies of the photochemistry of diazo carbonyl compounds J. Phys. Org. Chem. 23 308–14
[5] Jones R and Diels J-C 2001 Stabilization of Femtosecond Lasers for Optical Frequency Metrology and Direct Optical to Radio Frequency Synthesis Phys. Rev. Lett. 86 3288–91
[6] Wynne K and Carey J J 2005 An integrated description of terahertz generation through optical rectification , charge transfer , and current surge 256 400–13
[7] Hartl I, Li X D, Chudoba C, Ghanta R K, Ko T H, Fujimoto J G, Ranka J K and Windeler R S 2001 Ultrahigh-resolution optical coherence tomography using continuum generation in an air-silica microstructure optical fiber. Opt. Lett. 26 608–10
[8] Sakakibara Y, Rozhin A G, Kataura H, Achiba Y and Tokumoto M 2005 Carbon nanotube-poly(vinylalcohol) nanocomposite film devices: Applications for femtosecond fiber laser mode lockers and optical amplifier noise suppressors Japanese J. Appl. Physics, Part 1 Regul. Pap. Short Notes Rev. Pap. 44 1621–5
[9] Wang F, Rozhin a. G, Sun Z, Scardaci V, Penty R V., White I H and Ferrari a. C 2008 Fabrication, characterization and mode locking application of single-walled carbon nanotube/polymer composite saturable absorbers Int. J. Mater. Form. 1 107–12
[10] Chiu J, Chang C, Hsieh B, Lin S, Yeh C, Lin G, Lee C, Lin J and Cheng W 2011 Pulse shortening mode-locked fiber laser by thickness and concentration product of carbon nanotube
based saturable absorber 19 4036–41

[11] Hasan T, Sun Z, Wang F, Bonaccorso F, Tan P H, Rozhin A G and Ferrari A C 2009 Nanotube - Polymer composites for ultrafast photonics Adv. Mater. 21 3874–99

[12] Martinez A, Fuse K, Xu B and Yamashita S 2010 Optical deposition of graphene and carbon nanotubes in a fiber ferrule for passive mode- locked lasing Opt. Express 18 2242–4

[13] Wang F, Rozhin A G, Sun Z, Scardaci V, White I H and Ferrari A C 2008 Soliton fiber laser mode-locked by a single-wall carbon nanotube-polymer composite Phys. Status Solidi Basic Res. 245 2319–22

[14] Scardaci V, Sun Z, Wang F, Rozhin A G, Hasan T, Henrich F, White I H, Milne W I and Ferrari A C 2008 Carbon nanotube polycarbonate composites for ultrafast lasers Adv. Mater. 20 4040–3

[15] Muhammad F D 2014 GRAPHENE AS SATURABLE ABSORBER FOR PHOTONICS APPLICATIONS (University of Malaya)

[16] Chiu J, Lan Y, Chang C, Chen X, Yeh C, Lee C, Lin G, Lin J and Cheng W 2010 Concentration effect of carbon nanotube based saturable absorber on stabilizing and shortening mode-locked pulse Opt. Express 18 3592–600

[17] A Jorio, M A Pimenta, A G Souza Filho, R Saito G D and M S D 2012 Characterizing carbon nanotube samples with resonance Raman scattering New J. Phys. 5 1–11

[18] Fu L and Yu a M 2014 Carbon Nanotubes Based Thin Films: Fabrication, Characterization and Applications Rev. Adv. Mater. Sci 36 40–61

[19] Kwon C H, Chun K-Y, Kim S H, Lee J-H, Kim J-H, Lima M D, Baughman R H and Kim S J 2015 Torsional behaviors of polymer-infiltrated carbon nanotube yarn muscles studied with atomic force microscopy Nanoscale 7 2489–96

[20] Souier T, Stefancich M and Chiesa M 2012 Characterization of multi-walled carbon nanotube–polymer nanocomposites by scanning spreading resistance microscopy Nanotechnology 23 405704

[21] Mou C, Arif R, Rozhin A and Turitsyn S 2012 Passively harmonic mode locked erbium doped fiber soliton laser with carbon nanotubes based saturable absorber Opt. Mater. Express 2 884–90

[22] Agrawal G 2008 Chapter 5 – Fiber Lasers Applications of Nonlinear Fiber Optics (Academic Press) pp 179–244

[23] Collings B C, Bergman K, Cundiff S T, Tsuda S, Kutz J N, Cunningham J E, Jan W Y, Koch M and Knox W H 1997 Short cavity erbium/ytterbium fiber lasers mode-locked with a saturable Bragg reflector IEEE J. Sel. Top. Quantum Electron. 3 1065–74

[24] Rozhin A G, Sakakibara Y, Namiki S, Tokumoto M, Kataura H and Achiba Y 2006 Sub-200-fs pulsed erbium-doped fiber laser using a carbon nanotube-polyvinylalcohol mode locker Sub-200-fs pulsed erbium-doped fiber laser using a carbon nanotube-polyvinylalcohol mode locker 051118 1–4

[25] Yu Z, Wang Y, Zhang X, Dong X, Tian J and Song Y 2014 A 66 fs highly stable single wall carbon nanotube mode locked fiber laser Laser Phys. 24 15105

[26] Hua D, Su J, Cui W, Yan Y and Jiang P 2014 All-fiberized SBS-based high repetition rate sub-nanosecond Yb fiber laser for supercontinuum generation Laser Phys. Lett. 11 125103

[27] Sun Z, Rozhin A G, Wang F, Hasan T, Popa D, O’Neill W and Ferrari A C 2009 A compact, high power, ultrafast laser mode-locked by carbon nanotubes Appl. Phys. Lett. 95 2009–11

[28] Dupriez P, Piper A, Malinowski A, Sahu J K, Ibsen M, Thomsen B C, Jeong Y, Hickey L M B, Zervas M N, Nilsson J and Richardson D J 2006 High average power, high repetition rate, picosecond pulsed fiber master oscillator power amplifier source seeded by a gain-switched laser diode at 1060 nm IEEE Photonics Technol. Lett. 18 1013–5