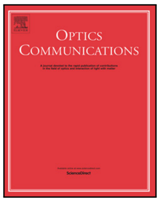
Optics Communications 413 (2018) 249–254

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom



Low threshold L-band mode-locked ultrafast fiber laser assisted by microfiber-based carbon nanotube saturable absorber

K.Y. Lau [a], E.K. Ng [a], M.H. Abu Bakar [a], A.F. Abas [b], M.T. Alresheedi [b], Z. Yusoff [c], M.A. Mahdi [a,*]

[a] *Wireless and Photonic Networks Research Centre, Faculty of Engineering, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia*
[b] *Department of Electrical Engineering, College of Engineering, P.O. Box 800, King Saud University, Riyadh 11421, Kingdom of Saudi Arabia*
[c] *Faculty of Engineering, Multimedia University, 63100 Cyberjaya, Selangor, Malaysia*

ARTICLE INFO

Keywords:
Ultrashort pulse
Pulsed fiber laser
Carbon nanotube

ABSTRACT

We demonstrate a passively mode-locked erbium-doped fiber laser in L-band wavelength region with low mode-locking threshold employing a 1425 nm pump wavelength. The mode-locking regime is generated by microfiber-based saturable absorber using carbon nanotube-polymer composite in a ring cavity. This carbon nanotube saturable absorber shows saturation intensity of 9 MW/cm^2. In this work, mode-locking laser threshold is observed at 36.4 mW pump power. At the maximum pump power of 107.6 mW, we obtain pulse duration at full-width half-maximum point of 490 fs and time bandwidth product of 0.33, which corresponds to 3-dB spectral bandwidth of 5.8 nm. The pulse repetition rate remains constant throughout the experiment at 5.8 MHz due to fixed cavity length of 35.5 m. Average output power and pulse energy of 10.8 mW and 1.92 nJ are attained respectively through a 30% laser output extracted from the mode-locked cavity. This work highlights the feasibility of attaining a low threshold mode-locked laser source to be employed as seed laser in L-band wavelength region.

1. Introduction

Silica fiber possesses low attenuation at third communication window that ranges from 1525 to 1615 nm wavelength. The conventional band (C-band; 1525–1565 nm) is the early generation wavelength range that supports telecommunications. In order to support higher demand of bandwidth, a long-haul wavelength range (L-band; 1570–1615 nm) is introduced [1]. This L-band plays significant role not only limited to telecommunications but other applications as well. This includes ultrafast mode-locked lasers which are exploited in an array of applications, such as gas spectroscopy [2] and optical microscopy [3]. The mode-locked laser is generated by either active mode-locking or passive mode-locking approach. Cavity loss can be modulated actively using an intra-cavity element such as acousto-optic modulator, or altered passively by incident radiation using a non-linear element, such as saturable absorber (SA). The latter mode-locking technique is simpler since no external synchronized driving circuits are required to perform loss modulation [4,5].

The function of SA is to absorb incoming photons at low intensity and transmits photons due to reduced optical loss at high intensity. This feature is unique to SA as an intensity dependent modulator. A faster recombination rate than absorption rate due to the ultrafast recovery time of the SA eventually saturates the excited photons at the edge of conduction band, while leaving the valence band empty. Eventually, the SA transmits photons at high intensity due to absorption saturation phenomenon. A semiconductor saturable absorber mirror (SESAM) was first proposed by Keller et al. to initiate passive mode-locked laser [6]. SESAM is of high interest for research investigation due to its feasibility of defect engineering and micro-fabrication growth [7]. However, high operational cost and procedural difficulties upon the fabrication process of SESAM drive the efforts of passive mode-locked laser using carbon nanotube (CNT) materials [8–10].

In material aspects, CNT possesses strong third-order nonlinearity [11] and ultrafast recovery time [12] which is favorable properties for pulsed fiber lasers. In the early deployment of CNT as saturable absorbers, this material is deposited directly on fiber core by spraying [8,9], direct synthesis [10], thin-film [13,14] and optical deposition [15,16]. The deposited CNT is placed between two fiber ferrules (sandwich-structured SA). However, the deposited CNT material within the fiber core region is exposed to high intensity pulse during the operation. Since the SAs are based on strong absorption

---

[*] Corresponding author.
E-mail address: mam@upm.edu.my (M.A. Mahdi).

https://doi.org/10.1016/j.optcom.2017.12.056
Received 11 October 2017; Received in revised form 6 December 2017; Accepted 20 December 2017

of light, this phenomenon leads to low thermal damage in which the materials are burnt out [17]. In order to mitigate this drawback, SAs using evanescent field interaction between light and CNT are proposed; ring-type deposition on fiber core [18], side-polished fiber [19], and microfiber [20]. The microfiber has advantages in terms of polarization insensitivity, high thermal damage threshold and longer light interaction region. Nevertheless, the CNT directly sprayed on microfiber [20] faces significant loss due to scattering. In order to improve this loss, the microfiber is encapsulated with dispersed CNT in low refractive index polymer (polydimethylsiloxane) [21]. In addition, the polymer composite provides protection from environmental contamination and mechanical support to make this CNT-SA more rugged and robust.

Although microfiber-based CNT-SA has been introduced since 2007, it has not been utilized to generate soliton pulses in the L-band region. Up to date, a few published articles reported the generation of femtosecond soliton pulses using thin-film based CNT-SAs [22,23]. Based on these works, the thin-film based CNT-SAs show mode-locking threshold at 150 mW [22] and 270 mW [23]. The mode-locking threshold is directly influenced by saturation intensity (I_{sat}). Indeed, I_{sat} is reported at 17 MW/cm^2 in [22] and 69 MW/cm^2 in [23]. Therefore, research interest is to improve the mode-locking threshold in L-band region by utilizing a SA with lower I_{sat}. In this paper, we demonstrate an L-band mode-locked fiber laser utilizing CNT-based microfiber SA with I_{sat} at 9 MW/cm^2. Correspondingly, mode-locked threshold is observed at 36.4 mW which shows spectacular improvement over previous works.

2. Optical characterization of CNT-SA

The initial experiment in this work is to optically characterize the microfiber-based CNT-SA received from K. Kieu from University of Arizona. The fabrication process of the CNT-SA is similar to the steps reported in [24]. Tapering was performed on a single mode fiber around 30 mm to 50 mm long with tapered diameter between 3 μm and 7 μm. The small diameter leads to large evanescent field around the tapered region. This region interacted with the CNT-polymer composite that was prepared by mixing low refractive index silicone elastomer (polydimethylsiloxane) with commercially available CNT using standard magnetic stirrer for 24 h. Then, the tapered fiber was placed inside the groove of a polymer substrate using epoxy glue. The prepared CNT-polymer composite was then poured into the groove to cover the tapered fiber. This device was then cured for 12 h until it was hardened. Finally, this architecture was sealed inside a metallic sleeve for mechanical protection. Since all these steps were performed beforehand at University of Arizona, we did not have the privilege of performing any physical or material characterizations. In this work, nonlinear saturable absorption properties of this CNT-SA are characterized before inserting it in the laser cavity. The characterization of SA is based on the balanced twin detector measurement scheme. In our experiment, a MenloSystem pulsed laser source at 1550 nm wavelength with repetition rate and pulse duration of 250 MHz and 117 fs respectively is deployed as the test source. A variable optical attenuator (VOA) is positioned after the pulsed laser source to adjust the input optical intensity. An inline optical isolator is inserted at the output port of the VOA to avoid the revert oscillation of pulsed laser signal back to the test source. A 3-dB optical coupler is then employed next to the isolator to divide the pulsed laser signal into two equal portions, with one arm measuring the power-dependent transmission of CNT-SA and the other arm for reference measurement.

The corresponding power dependent nonlinear saturable absorption curve of CNT-SA is depicted in Fig. 1. From this figure, the modulation depth (MD) is determined from the difference between initial transmittance at 52.2% until this CNT-SA is saturated at 54.7% transmittance under high peak power intensity. The measured MD of this CNT-SA is 2.5%, which is comparable to CNT-SA with MD of 2.54% as reported in [25]. Saturation intensity is the point where SA starts to reflect the light with high intensities at semi-absorption value of an unbleached SA [19]. For this CNT-SA, the saturation intensity is characterized at 9 MW/cm^2. This value is lower than reported values based on CNT-SA; 17 MW/cm^2 [22] and 69 MW/cm^2 [23]. Based on this analysis, the mode-locked laser can be generated easily at lower pump power threshold using this CNT-SA. For SAs utilizing similar material, the thickness of the deposited layer plays a crucial role in determining the saturation intensity as thinner SA material layer yields lower saturation intensity leading to lower mode-locking threshold [26]. Non-saturable loss is the redundant loss induced by an SA without exhibiting saturable absorption. It is a contributor to the total cavity loss of a laser setup. The non-saturable loss of our CNT-SA is measured at 45.3%, which is lower than 47.0% [27] and 59.2% [28], respectively. Since mode-locking threshold can only commence after CW operation, it is important to attain low non-saturable loss and saturation intensity in order to initiate mode-locked operation at low threshold.

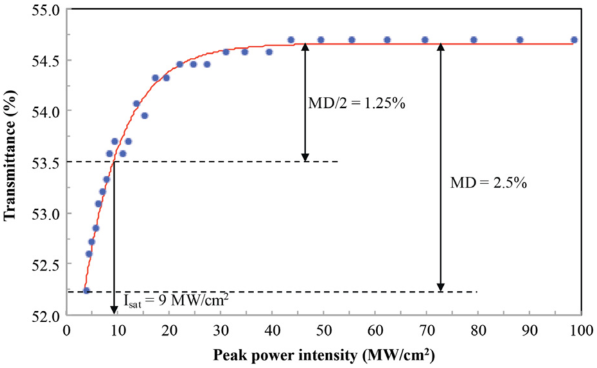


Fig. 1. Power-dependent nonlinear saturable absorption curve of CNT-SA.

3. L-band mode-locked fiber laser

Fig. 2 illustrates the schematic diagram of L-band mode-locked fiber laser. A section of 17 m highly doped erbium-doped fiber (EDF, Liekki Er80-8/125) with peak core absorption of 45 dB/m and 80 dB/m at 1400 nm and 1530 nm respectively is counter-pumped by a 1425 nm FITEL laser diode (LD) through a 1400/1550 nm wavelength division multiplexer (WDM). A polarization independent isolator (ISO) is employed to ensure counter-propagating configuration of EDF in clockwise direction of the laser cavity. The 1550 nm port of the WDM is then connected to the input port of an optical coupler (OC). In this case, X% of the oscillating laser signal is extracted out, whereas the remaining laser signal $[(1 - X)\%]$ propagates in the cavity towards a polarization controller (PC). A PC is used to tune cavity birefringence effect, which is then connected to a CNT-SA. The CNT-SA serves as passive mode-locker by synchronizing phase-locked longitudinal modes, results in Fourier transform-limited pulse. The CNT-SA is finally spliced to the input of the ISO to complete the cavity. The spectral measurement of L-band mode-locked EDFL is observed through a Yokogawa AQ6370B OSA with a resolution bandwidth of 0.02 nm.

For any laser systems, the cavity loss is important to determine the laser performance. In this work, the variation of cavity loss is achieved by changing the coupling ratio (CR) of the OC. Firstly, the optimization of OC is performed in order to obtain the lowest threshold for mode-locking operation using the SWCNT-SA. In this work, the CR is the term used to represent the percentage of oscillating light in the cavity as indicated by $(1 - X)\%$ in Fig. 2. This term is varied from 10% to 90% with a step of 10%. By changing the CR value, the total cavity loss is also altered accordingly. The other components in the cavity are unchanged throughout the experiment to ensure the same propagation loss whilst simultaneously minimizing the effect of dispersion. Fig. 3(a) shows the output spectrum of L-band mode-locked EDFL at mode-locking pump power threshold for each CR value. The central lasing