Mode-locked soliton erbium-doped fiber laser using a single-walled carbon nanotubes embedded in polyethylene oxide thin film saturable absorber

F. Ahmad, S.W. Harun, R.M. Nor, N.R. Zulkepely, F.D. Muhammad, H. Arof & H. Ahmad

Faculty of Engineering, Department of Electrical Engineering, University of Malaya, Kuala Lumpur, Malaysia
Photonic Research Centre, University of Malaya, Kuala Lumpur, Malaysia
Physics Department, University of Malaya, Kuala Lumpur, Malaysia

Published online: 25 Mar 2014.


To link to this article: http://dx.doi.org/10.1080/09500340.2014.899644
Mode-locked soliton erbium-doped fiber laser using a single-walled carbon nanotubes embedded in polyethylene oxide thin film saturable absorber

F. Ahmad\textsuperscript{a}, S.W. Harun\textsuperscript{a,b,*}, R.M. Nor\textsuperscript{c}, N.R. Zulkepely\textsuperscript{c}, F.D. Muhammad\textsuperscript{b}, H. Arof\textsuperscript{a} and H. Ahmad\textsuperscript{b}

\textsuperscript{a}Faculty of Engineering, Department of Electrical Engineering, University of Malaya, Kuala Lumpur, Malaysia; \textsuperscript{b}Photonic Research Centre, University of Malaya, Kuala Lumpur, Malaysia; \textsuperscript{c}Physics Department, University of Malaya, Kuala Lumpur, Malaysia

(Received 29 December 2013; accepted 25 February 2014)

We demonstrate a simple, compact, and low cost mode-locked erbium-doped fiber laser (EDFL) using a single-walled carbon nanotubes (SWCNTs) embedded in polyethylene oxide (PEO) thin film as a passive saturable absorber (SA). The film with a thickness of 50 \mu m was fabricated using a prepared homogeneous SWCNT solution with 0.1\% loading percentage, which was mixed with a diluted PEO solution and casted onto a glass Petri dish to form a thin film by evaporation technique. The film is sandwiched between two fiber connectors to construct a SA, which is then integrated in an EDFL cavity to generate a self-started stable soliton pulses operating at 1558 nm. The soliton pulse starts to lase at pump power threshold of 17.6 mW with a repetition rate of 50 MHz, pulse width of 0.67 ps, average output power of 0.158 mW, pulse energy of 3.16 pJ, and peak power of 4.43 W.

Keywords: single-walled carbon nanotubes; mode-locking; passive saturable absorber

1. Introduction

Passively mode-locked erbium-doped fiber lasers (EDFLs) have many applications ranging from basic research to telecommunications, medicine, and materials processing because of their simple and compact design, and high quality pulse generation. They usually operate at a high repetition rate above 10 MHz with a short pulse width in the range of femtoseconds to tens of picoseconds. The most widely utilized mode-locking technology includes a nonlinear polarization rotation (NPR) \cite{1,2}, semiconductor saturable absorber mirror (SESAM) \cite{3}, and carbon nanotubes \cite{4}. The method of NPR strongly depends on the polarization evolution and phase evolution of the optical pulse in the laser cavity; so in a long cavity, it can be easily overdriven and affected by the environment-induced fiber birefringence. SESAM technology is superior to NPR especially in ultra-long cavity mode-locking because its saturable absorption is independent of the cavity length. It is currently the dominating passive mode-locking technique in spite of their complex fabrication and narrow tuning range. Recently, a simple and cost-effective alternative, the use of single-walled carbon nanotubes (SWCNTs) has also attracted considerable attention, owing to its advantages, such as ultrafast recovery time, large saturable absorption, ease of fabrication, and low cost.

Carbon nanotubes can be embedded in various composite materials such as metal \cite{5}, ceramic \cite{6}, and polymer \cite{7}. In the recent years, carbon nanotubes’ polymer composites are the most extensively investigated due to the ease of handling as well as the carbon nanotubes’ properties are preserved during processing. They can be produced using various methods such as solution mixing \cite{8}, melt blending \cite{9}, and \textit{in situ} polymerization \cite{10} and have been employed for many applications such as \textit{pH} sensor \cite{11}, actuators \cite{12}, and strain sensors \cite{13}. Recently, carbon nanotubes’ polymer composite has also been produced in the form of transparent thin films \cite{14}. Some of the approaches reported to develop the film are: filtering \cite{13}, coagulation \cite{15}, and evaporation technique \cite{16}. Among them, the evaporation technique is the most cost effective and simplest approach, which can be achieved by mixing the nanotubes with water-soluble polymer and the evaporation process is either using low-temperature ovens or simply letting it to dry at room temperature \cite{16}. To date, many works have been reported on the fabrication of a high optical quality SWCNTs polyvinyl alcohol (PVA) composite film for laser mode-locking applications \cite{17,18}. For instance, Wang et al. \cite{17} use the SWCNTs-PVA composite saturable absorber (SA) as mode-locker in an EDFL and achieve ~0.56 ps pulse generation with good jitter performance and long-term stability.

Compared to PVA, polyethylene oxide (PEO) possesses a lower melting point and thus most researchers use PEO to disperse multi-walled carbon nanotubes (MWCNTs). For instance, Park et al. \cite{19} demonstrated MWCNTs–PEO composite film using the evaporation

\*Corresponding author. Email: swharun@um.edu.my

© 2014 Taylor & Francis
technique to make use of low melting temperature of PEO. In this paper, a passive mode-locked EDFL is demonstrated using a SWCNTs-PEO composite film-based SA. The SWCNTs-PEO film is developed using the similar technique as the earlier work [19]. The SA is constructed by sandwiching the film between two fiber connectors. It is incorporated in an EDFL system to demonstrate a soliton fiber laser which produces a train of 0.67 ps pulses. It has a lasing pump power threshold of 27 mW, which is lower than the previous SWCNTs-PVA-based mode-locked EDFL [17].

2. Experimental arrangement

A homogeneous suspension was prepared by mixing 250 mg SWCNTs (99% pure, diameter of 1–2 nm, and length of 3–30 μm) with 400 ml of 1% sodium dodecyl sulfate (SDS) solution in deionized water, and then ultrasonicating it for 30 min at 50 W. Dispersion of SWCNTs was achieved ultrasonically aided by SDS solution. The solution was centrifuged at 1000 rpm to remove large particles of undispersed CNT to obtain dispersed suspension that is stable for weeks. SWCNTs-PEO composite was fabricated by adding 1.8 ml dispersed SWCNTs suspension containing 1.125 mg solid PEO into a solution of 1 g PEO (average molecular weight of 1 × 10^6 g/mol) in deionized water and thoroughly mixed. The SWCNTs-PEO composite was fabricated by cutting a small part of the fabricated SWCNTs-PEO composite, respectively. The insertion loss of the SA is measured to be around 6 dB at 1550 nm. The gain medium is a 3 m long erbium-doped fiber (EDF) with the absorption coefficient of approximately 11 dBm^{-1} and group velocity dispersion (GVD) of −21.64 ps/nm/km at 1550 nm. A 980 nm laser diode is used to pump the EDF through a 980/1550 wavelength division multiplexer (WDM). The WDM comprises 0.5 m HI1060 nm pigtailed fiber with a GVD of −38 ps/nm/km. The single-mode fiber (SMF) that make up the rest of ring cavity have a total length of 5 m with GVD of 18 ps/nm/km.

The total net cavity dispersion is estimated to be around 0.006 ps/nm at 1550 nm. An isolator is incorporated in the laser cavity to ensure the unidirectional propagation. The output of the laser is tapped out from the cavity via a 95/5 fiber coupler. The output is analyzed using an optical spectrum analyzer with a resolution of 0.02 nm and a 500 MHz oscilloscope with 6 GHz bandwidth light wave detector. All components used in our setup are polarization independent, i.e. they support any light polarization. No polarization controller (PC) is included in the laser cavity as we had observed earlier that a PC did not improve our pulse stability. There was no significant pulse jitter observed through the oscilloscope during the experiment. The total length of the laser cavity is estimated to be around 8.5 m.

3. Results and discussion

Figure 4 shows the optical spectrum of the mode-locked fiber laser obtained using the prepared SWCNT–PEO-based SA at 980 nm pump power of 29
mW. It exhibits spectral sidebands which are typical characteristics of soliton pulses under periodic perturbations. This confirms the attainment of the anomalous dispersion and the formation of the soliton pulse, which is due to the inter-correlation between the dispersion and nonlinearity of the intra-cavity medium. The mode-locking operation is also observed to self-start at the pump power as low as 17.6 mW without the requirement to introduce any disturbance to the intra-cavity fiber and even without the employment of a PC. This indicates that the self-starting mode-locked operation could be initiated regardless of the polarization state, and correspondingly, in order to maintain the mode-locking performance, there is no necessity to control the PC, which means that the mode-locking operation in our setup is polarization independent. As shown in Figure 4 the central wavelength of the laser...

Figure 2. Schematic configuration of EDFL passively mode-locked by SWCNTs-PEO film-based SA.

Figure 3. SWCNTs-PEO film-based saturable absorber: (a) the attachment of the film on the fiber ferrule and (b) integration of SWCNT composite film in laser cavity. (The colour version of this figure is included in the online version of the journal.)

Figure 4. Optical spectrum of the mode-locked fiber laser at pump power of 29 mW. (The colour version of this figure is included in the online version of the journal.)
output with a soliton-like spectrum is measured to be approximately 1558 nm with a 3 dB spectral bandwidth of 5 nm, comparable with the 3 dB bandwidth reported in the other research works using the SWCNT-based SA [20] as well as graphene-based SA [21,22].

Figure 5 shows the pulse train of the passive mode-locked laser obtained at pump power of 29 mW. It has a time interval of 20 ns between the pulses, corresponding to a pulse repetition rate of 50 MHz. Multiple solitons are generated as identified in the pulse train, which is due to soliton energy quantization [23]. The high repetition rate obtained is due to the multiple pulses circulating inside the cavity to generate harmonics mode-locked fiber laser. The major factors in creating this phenomenon are interrelated with the peak power limiting effect of the laser cavity besides the gain competition between the multiple solitons [24]. This proves that the SWCNT-PEO film-based SA is able to operate efficiently in the ring EDFL. Figure 6 represents the second harmonic generation autocorrelation trace, with the estimated pulse duration of 0.67 ps at its full-width half maximum (FWHM). The sech² fitting which indicates the generation of the soliton pulse is also included in the figure. The autocorrelation trace reveals that the experimental result follows the sech² fitting closely. As shown in the figure, the experimental spectrum shows two peaks in between the central peak which indicates that the pulse train is composed of a train of bound state of two pulses. With an average output power of 0.158 mW, this SWCNTs-based mode-locked EDFL yields pulse energy of 3.16 pJ and peak power of about 4.43 W.

A time-bandwidth product (TBP) of 0.39 calculated from the 3 dB bandwidth of the optical spectrum and the FWHM of the pulse is slightly higher than the expected transform limited value of 0.315, which is the standard temporal profile for a sech² pulses. The difference between the TBP obtained from our experiment with the expected value for transform limited sech² pulse is probably due to presence of chirping in the pulse [15], which originates from the remaining dispersion of the laser cavity [15]. Based on theory, an accurate value of 0.315 for the transform limited sech² pulse could only be realized in the chirp-free sech² pulses [16], which is somehow quite challenging. Besides that, the extension of the SMF which is connected to the laser output also influences the estimated TBP value [14]. Stability test has shown that the laser can operate continuously for days without losing mode-locking. This might be contributed to the good thermal properties of our composite film. Inset shows the radio frequency (RF) spectrum of the mode-locked laser output, which indicates the fundamental repetition rate of 50 MHz. The fundamental peak to the pedestal extinction is estimated to be approximately 52 dB, which indicates the stability of the laser.

![Figure 5](image1.png)

**Figure 5.** Output pulse train with a repetition rate of 50 MHz. (The colour version of this figure is included in the online version of the journal.)

![Figure 6](image2.png)

**Figure 6.** Autocorrelation trace with FWHM of 0.67 ps. Inset shows the RF spectrum of the mode-locked output. (The colour version of this figure is included in the online version of the journal.)
4. Conclusion
We have experimentally demonstrated a passive mode-locked EDFL using a SWCNTs-PEO composite thin film-based SA. The film is fabricated using a prepared homogeneous SWCNT's solution with about 0.1% SWCNT loading by the solution casting technique which was mixed with a diluted PEO solution and casted onto a glass Petri dish forming a thin film with 50 μm thickness by evaporation technique. It is then integrated in laser cavity by attaching to the end of fiber ferrule with the aid of index matching gel. The fiber laser generates soliton pulses with 50 MHz repetition rate, 0.67 ps pulse width, average output power of 0.158 mW, pulse energy of 3.16 pJ, and peak power of 4.43 W.

Funding
The authors acknowledge the financial support from the University of Malaya and Ministry of Higher Education (MOHE) under various grant schemes [grant number RP008C-13AET], [grant number PG139-2012B], [grant number ER012-2012A].

References