Generation of an ultrafast femtosecond soliton fiber laser by carbon nanotube as saturable absorber

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Abstract. This paper reports the demonstration of ultrafast fiber laser in a simple erbium-doped fiber (EDF) laser that employed a carbon nanotube (CNT) thin film saturable absorber (SA) to generate a stable soliton pulse. The repetition rate of 10.8 MHz pulse consistently achieved has narrowest pulse width of 640 fs and 1555.78 nm central wavelength for an hour operation in room temperature. This proposed setup has the capability for reliable and stable system features.

1. Introduction

Passively ultrafast femtosecond erbium-doped fiber laser (EDFL) with its uniqueness and compactness has gained a wide attention in pulse fiber laser application. A pulse laser has opened up an extensive variety of laser applications, for instance supercontinuum generation [1, 2], laser marking and cutting [3] and non-linear nonlinear frequency conversion [4, 5]. Pulse laser has been reported to have a low cost deployment and well known for their flexibility design [6, 7].

A number of techniques have been widely reported to generate passive ultrafast femtosecond soliton fiber laser. One of the effective methods is to use an optical material in this case refer to saturable absorber (SAs), where at highest optical intensities the optical loss can be decreased. In the last decade, semiconductor saturable absorber mirror or SESAM has been a dominant SAs technology to produce passively Q-switched pulse [8, 9]. However, there are several drawbacks associated with SESAM as SAs for pulse laser. For example, SESAM requires expensive clean room facilities and have a very complex packaging and fabrication [10, 11]. In addition, they also suffer from the narrowband wavelength range [12]. In recent years, a carbon-based nanomaterials such as carbon nanotubes (CNTs) [12-14] and graphene [15, 16] have been introduced to overcome the limitation of SESAMs in Q-switching technology. CNT-based SAs are still in demand as they have interesting features such as simple fabrication process and ultrafast recovery time that make them as practical SAs for pulse laser application.
In this work, we demonstrated an ultrafast soliton mode locked EDFL by using CNT film as SA. The soliton spectrum was obtained at centered wavelengths of 1555.78 nm. The pulse repetition rates and pulse width obtained from the setup were 10.8 MHz and 640 fs respectively thus demonstrated the CNT characteristic of saturable absorption for EDFL mode locking operation.

2. Experimental Setup
In this experiment, mode locked setup is depicted in figure 1 which comprises of 50 cm of Liekki ER110-4/125 erbium doped fiber with 110 dB/m peak absorption at 1530 nm, a single mode fiber (SMF) and few layer carbon nanotube (CNT) based SA. The erbium-doped fiber was forward pumped by a Oclaro LC96A74P-20R laser diode (LD) with 974 nm wavelength and 600 mW maximum pump power. The LD was coupled to the laser cavity via a 980/1550 nm wavelength division multiplexer (WDM). Then, a polarization insensitive isolator is incorporated into the laser cavity to avoid undesired backward reflection propagation and was attached to polarization controller (PC) and then was attached to few layers CNT, which functions as a SA, was sandwiched between two fiber ferrules. In this experiment, the preparation and fabrication of few layers CNT was detail explained in our previous work [17]. A 10-dB combined bi-conical optical coupler (OC1) was used to tap 10% of total power in-order to monitor the optical spectrum, power and mode locked pulses. 10% output port was afterwards attached to a 3-dB optical coupler (OC2) to enable simultaneous monitoring of pulse traces and wavelength spectrum. 90% output port was connected to 500 m SMF and then attached to WDM to complete cavity ring configuration. During the experiment, one of the output coupler was swapped to an OPM to measure the output power. A YOKOGAWA AQ6373 optical spectrum analyzer (OSA) with 0.02 nm resolutions and a fast Thorlabs D400FC photodetector were connected to YOKOGAWA DLM2054 digital oscilloscope to monitor the pulse train. A 9 kHz -7.8 GHz radio frequency spectrum analyzer (RFSA) model MS2683A by Anritsu is utilized to measure the pulse signal in frequency domain and an autocorrelator model HAC200 (ALNAIR) is used to measure the pulse width of soliton mode locked pulse.

![Figure 1. Schematic CNT based mode locked in the EDFL](image)

3. Results and Discussion
In this work the EDFL began its mode locked self-started operation at 80 mW pump power, as given in figure 2(a) obtained from the OSA, with soliton Kelly sidebands spectrum at 1555.78 nm and the output power of -36.74 dBm. Although the pump power was increased, a stable pulse train with constant repetition rates were observed by the oscilloscope as depicted in figure 2 (b) with repetition rates of 10.8 MHz. The mode locked frequency was not relying on the pump power, as a common behavior of a passively Q-switched fiber laser. Furthermore, figure 2 (c) shows the pulse width was measured to be 640 fs.
fs (full width at half maximum) using autocorrelator. Figure 2 (d) records the frequency domain of the pulse train, achieved from a radio frequency spectrum analyzer (RFSA). The spectrums verify 10.8 MHz as the fundamental harmonic frequency with a 38 dB peak-to-pedestal ratio. Furthermore, the wideband of RFSA as given in figure 2 (d) shows no spectral modulation, implying a stable soliton mode locked pulse generated in the system.
Figure 2. The soliton mode locked characterization at 80 mW with (a) soliton Kelly sidebands spectrum, (b) pulse duration, (c) pulse width and (d) radio frequency output spectrum.
4. Conclusion

In summary, we have successfully achieved the soliton mode locked based CNT SA. The soliton Kelly sidebands spectrum was obtained at 1555.78 nm wavelength and repetition rate of 10.8 MHz with narrowest pulse width of 640 fs.

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