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Ultrafast soliton mode-locked Zirconia-based Erbium-doped fiber laser with carbon nanotubes saturable absorber

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Abstract. Ultrafast soliton mode-locked fiber laser was successfully generated in zirconia-yttria-alumina (Zr-Y-Al) co-doped erbium-doped fiber laser cavity using a single-wall carbon nanotubes (SWCNTs) as saturable absorber. The laser cavity was 11.5 m long with the group delay dispersion of -0.04 ps^2. The laser generates soliton pulse train with a center wavelength and 3 dB bandwidth of 1564.2 nm and 3.8 nm, respectively at pump power of 92 mW. Meanwhile, the repetition rate, pulse duration and pulse energy were 17.7 MHz, 770 fs and 51.4 nJ.

1. Introduction

In recent years, mode-locked erbium-doped fiber lasers (EDFLs) are being extremely explored due to their advantages such as flexibility, compact design and cost effective. They have potential scientific applications in many areas such as industry, military, medicine, remote sensing and optical communication [1-2]. Mode locked EDFLs are most commonly achieved by using passive modulation techniques for instance nonlinear polarization rotation (NPR) [3-4] and semiconductor saturable absorbers (SESAMs) [5-6], but either are costly or required some delicacy to implement, thus rendering the development of a compact ultrafast fiber laser impracticable. The use of carbon nanotubes (CNTs) and graphene material as passive saturable absorbers (SAs) has captured the interest of many researchers working on Q-switched and mode-locked fiber lasers [7-9]. This is due to a number of inherent advantages that they possess, including good compatibility with optical fibers, low saturation intensity, fast recovery time, and wide operating bandwidth [10-11].

CNT-based SAs are still popular as they are easier to fabricate [12]. Furthermore, CNT-based SAs may also have a lower non-saturable to saturable absorption ratio as compared to graphene [13]. With the outstanding quality and controllable physical parameters, CNT absorber fabrication technique is very practical for large, cost effective and high speed industrial production. A simple and cost effective fabrication technique of this SA was successfully demonstrated in a polymer matrix with implanted composite SWCNTs [14]. This technique easily adapted to the real application with the used of thin film formation due to outstanding homogenous dispersion of SWCNTs [15-16].

This paper demonstrates a soliton mode locked fiber laser in zirconia-yttria-alumina (Zr-Y-Al) co-doped erbium-doped fiber laser cavity using a simple, compact and cheap SWCNTs based SA. The SWCNTs having a large diameter precisely selected to operate at longer wavelength region of 1.5 µm and prepared using Polyvinyl alcohol (PVA) composite. The SA is designed by sandwiched together the composite film between two fiber connectors to generate mode-locked pulses with a pulse width of 770 fs as well as a repetition rate, average output power and pulse energy of 17.7 MHz, 0.91 mW and 51.4 nJ, respectively. The proposed mode locked operates at 1564 nm region which is desirable for many applications, such as optical communications by using all-fiber configuration.

2. Fabrication and Characterization of SWCNT SA

The main component of the proposed mode-locked laser is the SWCNTs-based SA, which is obtained by embedding SWCNTs into a poly (ethylene) oxide (PEO) film. It uses SWCNTs powder, which was synthesized by catalytic chemical vapour deposition (CCVD) process as raw material in the preparation. The SWCNTs grains were 99 % pure with a diameter of 1-2 nm and length of 3-30 µm and thus they required no purification process. In the experiment, 250 mg SWCNTs were added to 400 ml sodium dodecyl sulphate (SDS) solution in deionized water at 1 % concentration before being sonicated for 30 min at 50 W. The dispersion of single walled CNTs in the solution was achieved ultrasonically with the aid of SDS, which induced the dispersion of the grains as separate tubes in aqueous solution. The solution was centrifuged at 1000 rpm to remove large particles of undispersed SWCNT to obtain dispersed suspension that is stable for weeks.

The 1.8 ml of dispersed SWCNT suspension containing 1.125 mg solid SWCNT was then added into a polymer solution, which was obtained by mixing 1 g of polyethylene oxide (PEO, average molecular weight of 1 x 106 g/mol) with deionized water. The mixture was thoroughly mixed through a centrifuging process to form a SWCNTs-PEO composite precursor solution. Then the precursor solution was casted onto a glass petri dish and kept in a vacuum oven at 60 ^{o}C for 48 hours to form a thin film. The free standing film had a peak absorption at 1.5 µm with a thickness of around 50µm and was then used to form a fiber compatible SA device for mode-locking pulse generation in the proposed EDFL setup. The fabrication processes of the SWCNTs film is summarized in Figure 1. Figures 2 (a) and (b) show the ‘real’ and Field Emission Scanning Electron Microscopy (FESEM) images of the SA film, respectively. Figure 2 (b) indicates that the SWCNTs are randomly distributed in the polymer composite.

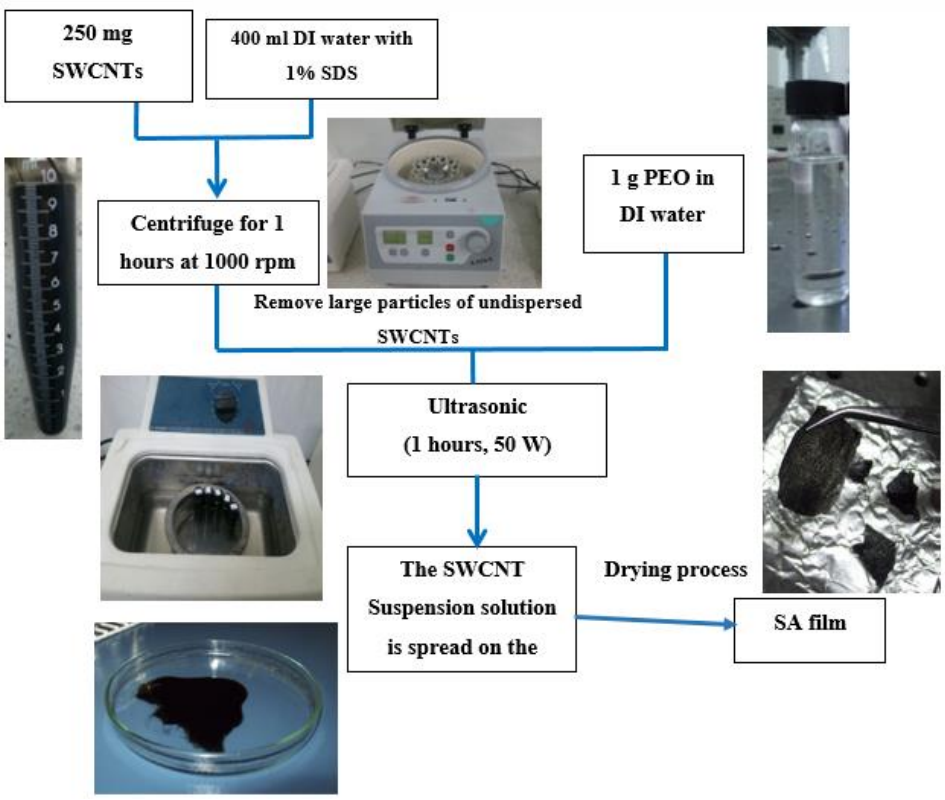

Figure 1. Fabrication procedures of SWCNTs-PEO.

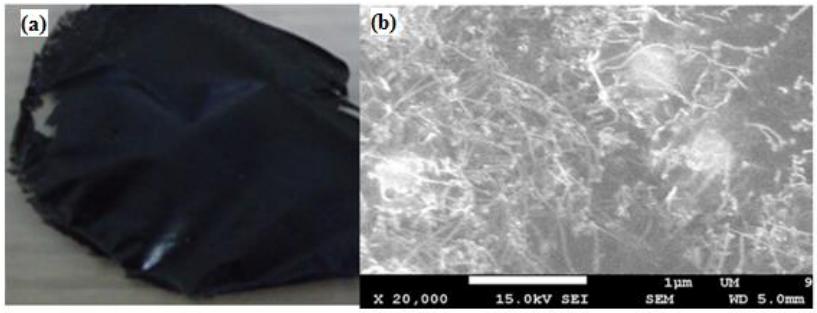

Figure 2. (a) An actual size and (b) FESEM images of the SWCNTs-PEO composite film.

Figure 3 shows the Raman spectrum, which was obtained using a Raman spectrometer where the small piece of the SA film was excited by a 532 nm laser. The spectrum can be used to confirm the presence of SWCNTs in the composite film and to determine the nanotube diameter distribution. As shown in the spectrum, the so-called G peak, which originates from the tangential vibrations of the carbon atoms, is prominent at 1584 cm^{-1}. In the low frequency region, the RBMs are observed, for which their energy is inversely related to SWCNT diameter. Since the distinct peaks are observed at around 214 cm^{-1}, the SWCNT diameter is estimated to be approximately 0.9 nm. This translates to the operating wavelength of around 1550 nm region. The carbon and G′ peaks are also observed at 1363 cm^{-1} and 2670 cm^{-1}, respectively.

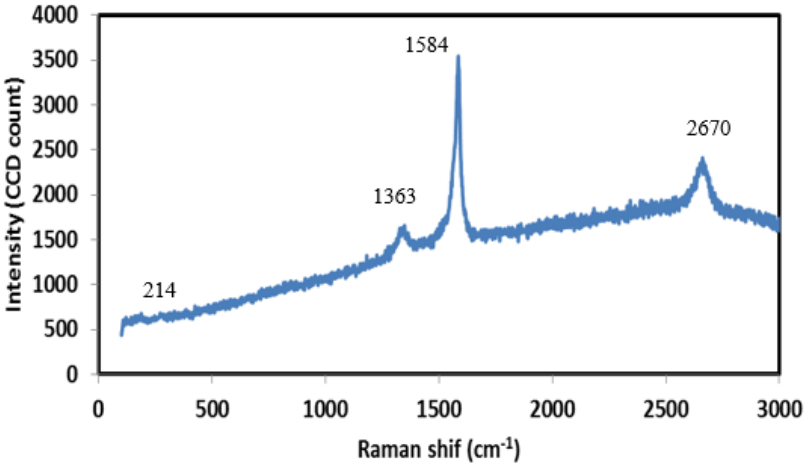

Figure 3. Raman spectrum of the prepared SWCNTs-PEO composite thin film.

3. Experimental Setup

The fiber laser setup used in the experiment is schematically shown in Figure 4. It is based on a ring configuration with the prepared SWCNTs-PEO SA was used as a mode-locker. The SA was fabricated by cutting a small part of the prepared composite film and sandwiching it between two FC/PC fiber connectors, after depositing index-matching gel onto the fiber ends. The insertion loss of the SA is measured at around 2 dB at 1550 nm. The gain medium is a 2 m long Zr-EDF with the absorption coefficient of approximately 220 dB/m and group velocity dispersion (GVD) of -56 ps^2/km at 1550 nm. A 980 nm laser diode is used to pump the Zr-EDF through a WDM. The WDM comprises 3 m long pigtailed fiber with a GVD of -38 ps^2/km at 1550 nm. The single mode fiber that makes up the rest of the ring cavity is 6.5 m in length with GVD of -21 ps^2/km. The estimated net dispersion and group delay dispersion (GDD) of the cavity, ignoring the GVD of the SA are 0.279 ps/nm and -0.04 ps^2, thus the cavity operates at the anomalous dispersion region. A PC is used to adjust the state of polarization in the cavity while a polarization independent isolator is incorporated in the laser cavity to force unidirectional propagation of light. The output of the laser is tapped from the cavity via a 95/5 output coupler, which keeps 98 % of the light oscillating in the cavity. An OSA with wavelength resolution of 0.02 nm is used to capture the output laser spectrum while a 350 MHz oscilloscope in conjunction with 1.2 GHz bandwidth photo-detector is used to detect the pulse train. The total length of the cavity is around 11.5 m.

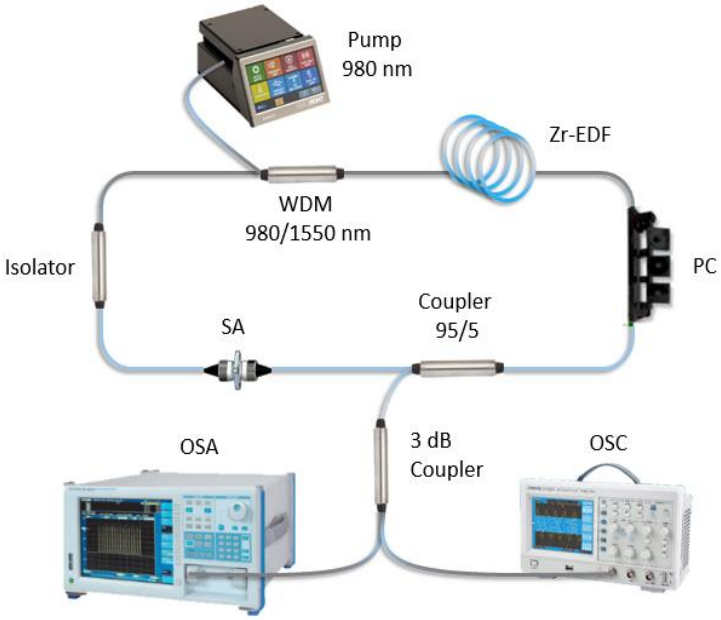

Figure 4. Schematic configuration of Zr-EDFL passively mode-locked by SWCNTs-PEO film-based SA.

4. Results and Discussion

It is observed that the laser always works in the CW operation with a threshold pump power of 45 mW in the absence of the SA in the cavity. As the SWCNT-based SA is incorporated in the laser cavity, the mode-locked laser self-started at pump power of 67 mW with appropriate setting of PC. Figure 5 shows the optical spectrum of the passively mode-locked Zr-EDFL at three different pump powers, analyzed by an OSA limited by a resolution of 0.02 nm. It operates at the central wavelength of 1564.2 nm and the 3 dB bandwidth is approximately 3.8 nm with strong Kelly sidebands at the maximum pump power of 92 mW. The spectrum is free from continuous wave (CW) parasitic lasing. The presence of Kelly sidebands confirms that this mode-lock fiber laser is operating in anomalous dispersion regime.

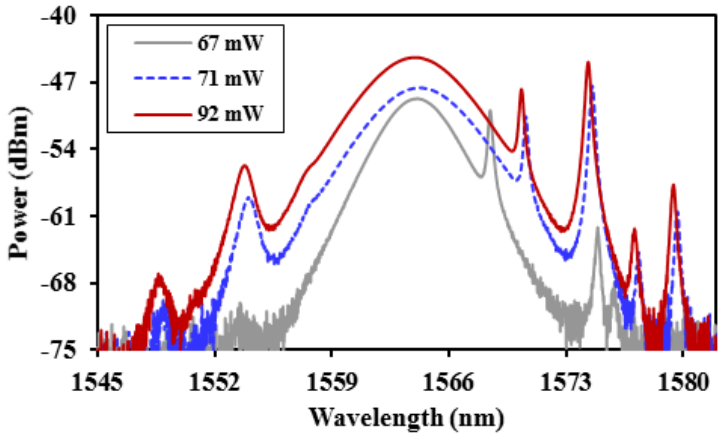

Figure 5. Output spectrum of the proposed mode-locked fiber laser at various pump powers.

Figure 6 (a) shows the pulse train of the passive mode-locked fiber laser obtained at pump power of 67 mW. It has a cavity round trip time of 56 ns, corresponding to a pulse repetition rate of 17.7 MHz and a cavity length of 11.5 m. Figure 6 (b) shows the corresponding second harmonic generation (SHG) autocorrelation trace, with the estimated pulse duration of 770 fs at its full-width half maximum (FWHM). A time-bandwidth product (TBP) calculated from the 3 dB bandwidth of the optical spectrum and the FWHM of the pulse is around 0.677, which indicates that the pulse is slightly chirped. The radio-frequency (RF) spectrum is shown in Figure 7. One can observe that the fundamental repetition rate of soliton is ~17.7 MHz. The peak-to-background ratio of the RF spectrum is 37.4 dB, implying a good mode-locking stability. At the maximum pump power of 92 mW, the output power for this fiber laser is 0.91 mW. Consequently, the resultant pulse energy is estimated to be around 51.4 nJ. We believe that the output power and pulse energy can be improved by reducing of the cavity loss and optimizing the output coupler. Based on the experiment results, we conclude that the fiber laser operates at a stable soliton mode-locking state.

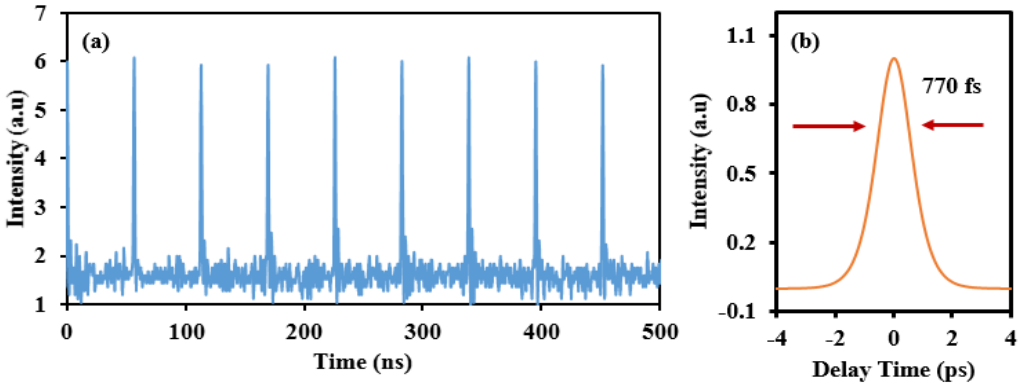

Figure 6. The temporal characteristics of the soliton laser (a) oscilloscope trace (b) autocorrelation trace.

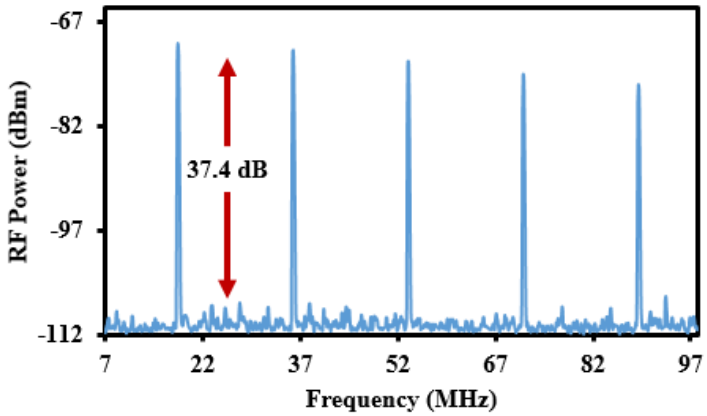

Figure 7. Radio-frequency spectrum of the soliton laser.

5. Conclusion

A mode-locked Zr-EDFL was demonstrated using a SWCNTs based SA to generate a soliton pulse operating at fundamental frequency of 17.7 MHz. The SA is obtained by sandwiching a piece of SWCNT-PEO film between two fiber connectors for passive mode-locking. The cavity operates at the anomalous dispersion region with a length of 11.5 m with estimated net group delay dispersion of -0.04 ps^2. The pulses are characterized by a slightly chirped pulse width of 770 fs, RF signal peak to noise ratio of 37.4 and pulse energy of 51.4 nJ at pump power of 92 mW.

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