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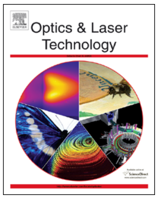

All fiber mode-locked Erbium-doped fiber laser using single-walled carbon nanotubes embedded into polyvinyl alcohol film as saturable absorber

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ABSTRACT

We experimentally demonstrate an all-fiber mode-locked Erbium-doped fiber laser (EDFL) using single walled carbon nanotubes (SWCNTs), which is embedded into polyvinyl alcohol (PVA) as a saturable absorber. The laser generates a self-starting dissipative soliton pulse, which operates in 1533.6 nm region without any additional spectral filter as a 980 nm pump power is increased above the threshold value of 35.2 mW, respectively. The output solitons have a pulse duration of 1.8 ps with a repetition rate of 15.3 MHz. At pump power of 71.0 mW, the pulse energy and peak power are approximately 0.28 nJ and 148 W.

1. Introduction

Research on passive mode-locked Erbium-doped fiber lasers (EDFLs) has thrived because of their compactness, flexibility, and low cost [1,2]. A number of approaches to produce ultrashort pulses like nonlinear optical loop mirror (NOLM) [3], nonlinear polarization rotation (NPR) [4,5] and passively mode-locking with saturable absorbers (SAs) [6–10] have been suggested. In the NOLM approach, a long fiber must be used to produce sufficient nonlinear phase shifts. The NPR technique utilizes dispersion and nonlinearity management to generate laser. However, it is often sensitive to ambient factors such as vibration and temperature, which limits its practical applications. The use of saturable absorbers such as semiconductor saturable mirrors (SESAMs) [10], carbon nanotubes (CNTs) [7,8], and graphene [9] have been proposed and demonstrated in passive mode-locking. However, SESAMs are costly, complex to fabricate, operate in narrow wavelength band, have a low damage threshold and long recovery time for ultra-short pulse generation. In contrast, CNT and graphene absorbers are cheaper and simpler to fabricate, operate in wider wavelength band, and have shorter recovery time.

CNT absorbers can be constructed in many forms, such as substrate based CNT absorber [10], solution based CNT absorber [11], evanescent field based CNT absorber [12], absorber with CNT on the fiber end [13] and so on. Each of these absorbers has inherent shortcomings that thwart widespread industrial applications. Substrate based CNT absorbers are usually thick and hard. Thus, they cannot be attached to fiber tips easily and require bulky collimation setup for integration within the fiber system. Solution based CNT absorbers require the use of a hollow fiber with a host solution with low optical loss and appropriate reflective index that is hard to find. Other issues related to solution based CNT absorbers are CNT aggregation and liquid evaporation. Evanescent field based CNT absorbers utilize tapered or side polished fiber that entails extra optical loss and cost. When the CNT layer is grown directly on the fiber end, its thickness cannot be controlled easily. Furthermore, a high purity CNT layer necessary for an absorber of this structure is difficult to produce via this method. This results in high nonsaturable losses.

A practical CNT absorber construction method suitable for industrial production must be cheap and fast where the output quality is consistent and the physical parameters are controllable. Recently, a simple and cost-effective alternative to fabricating a saturable absorber by using composite with embedded SWCNTs in a polymer matrix has been proposed [14]. This method is very promising since the composite exhibits excellent homogeneous dispersion of SWCNTs and it can be used in the form of a thin-film. For instance, all-fiber mode-locked Ytterbium doped fiber lasers (YDFLs) have been demonstrated using SWCNT embedded in polyvinyl alcohol (PVA) film [15,16]. Kobstev et al. [15] demonstrated a mode-locking pulse with a duration of 16 ps and repetition rate of 125 MHz operating at a wavelength of 1058 nm using SWCNTs with a diameter of 0.8 nm. Meanwhile Fedotov et al.

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[16] examined methods of controlling pulse duration, spectral width and wavelength of the mode-locked YDFL using a birefringent filter. In this paper, a mode-locked Erbium-doped fiber laser (EDFL) with a self-starting dissipative soliton is demonstrated using a simple and cheap SWCNT-based SA. This SA also was prepared using PVA as a host polymer but the raw SWCNTs used were of larger diameter specifically chosen to operate optimally at a longer wavelength region of 1550 nm. The SA was integrated in the EDFL ring cavity by sandwiching the SWCNT/PVA thin film between two fiber connectors to achieve a stable pulse train with 15.3 MHz repetition rate, 1.8 ps pulse width and 148 W peak power at 71.0 mW pump power in the 980 nm region.

2. Experimental procedure

In this work, the key element of mode-locking pulse generation is the fabrication of a saturable absorber incorporating dispersed SWCNTs. To match the EDFL operating at 1550 nm, choosing suitable SWCNTs with correct mean diameter and distributed diameter range is a critical step. In this work, we used SWCNTs with the purity of 99%, distributed diameter of 1–2 nm and length of 3–30 μm. The host material is PVA, which is a water-soluble synthetic polymer with monomer formula C_2H_4O. It has excellent film forming, emulsifying, and adhesive properties. It also has high tensile strength, flexibility, and high oxygen and aroma barrier, although these properties are dependent on humidity. Since it was difficult to disperse the SWCNTs in water, sodium dodecyl sulfate (SDS) solvent (average molecular weight of 288.38 g/mol) was used to prepare a homogeneous solution of the SWCNTs. SDS has the ability to disperse the SWCNTs with good dispersing stability in water. There were three major steps in the fabrication of the saturable absorber. First, we mixed the SWCNTs and dispersant in water to form the hybrid solution. We stirred the hybrid solution by using an ultrasonic cleaner for 1 h to uniformly disperse SWCNTs with suitable ratio of all inclusions. The solution was centrifuged at 1000 rpm to remove large particles of undispersed SWCNTs to obtain a dispersed suspension that is stable for weeks. Second, we prepared a PVA solution by dissolving 1 g of PVA in 400 ml of distilled water. Then we mixed the PVA solution with the hybrid SWCNTs solution to form a precursor which was stirred using an ultrasonic cleaner for about 1 h. This step was done to provide viscosity to the precursor so that it could be easily used in forming the SWCNTs–PVA film. Finally, suitable amounts of precursor were spread as a thin layer on the glass substrate, and left to dry at room temperature to form the saturable absorber film.

Raman spectroscopy was then performed on the film using laser excitation at 532 nm to confirm the presence of SWCNTs within the composite. Fig. 1 shows the obtained Raman spectrum showing the distinct feature of the SWCNT. The so-called G-peak, which originates from the tangential vibrations of the carbon atoms, is observed to be prominent at 1587.4 cm^{-1} indicating that the SWCNT has a semiconducting trait. Small peaks are also observed at 273.7 cm^{-1} which represents radial breathing mode (RBM) of the carbon nanotubes. Based on the Raman shift of the RBM, the SWCNT diameter is estimated to be around 1.3 nm. The carbon and G′-peaks are also observed at 1334 cm^{-1} and 2648 cm^{-1}, respectively.

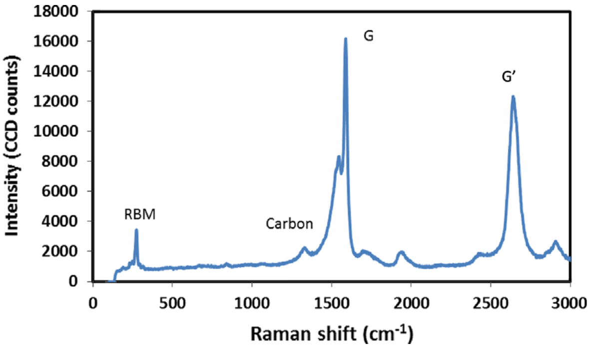

Fig. 1. Raman spectrum obtained from the fabricated SWCNTs–PVA film based SA.

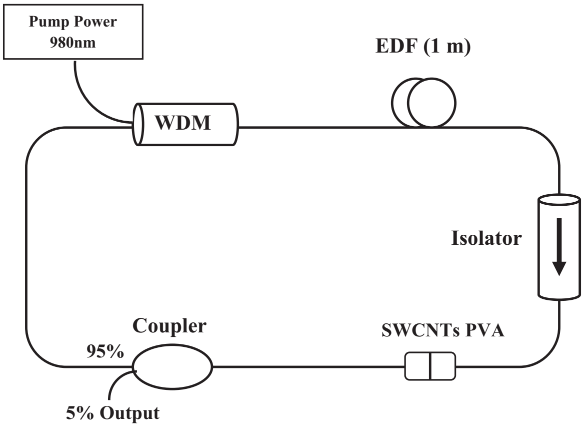

Fig. 2. Schematic configuration of the mode-locked EDFL.

The experimental setup of the proposed mode-locked EDFL is shown in Fig. 2, which consists of a 1 m long Erbium-doped fiber (EDF), a 980/1550 nm wavelength division multiplexer (WDM), an isolator, a SWCNTs–PVA film based SA, and 95/5 output coupler in a ring configuration. The SA is fabricated by cutting a small part of the earlier prepared film (2×2 mm^2) 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 to be around 1.5 dB at 1550 nm. The EDF has core and cladding diameters of 4 μm and 125 μm respectively, a numerical aperture of 0.16 and Erbium ion absorption of 23 dB/m at 980 nm. It is pumped by a 980 nm laser diode via the WDM. An isolator is incorporated in the laser cavity to ensure unidirectional propagation of the oscillating laser. The output of the laser is tapped out of the cavity through a 95/5 coupler which keeps 95% of the light to oscillate in the ring cavity. An optical spectrum analyzer is used to analyze the spectrum of the mode-locked EDFL with a spectral resolution of 0.02 nm whereas an oscilloscope and an autocorrelator are used to observe the output pulse train of the laser via a 460 kHz bandwidth photo-detector (Thor lab, PDA50B-EC). The total cavity length of the ring resonator is measured to be around 11 m.

3. Result and discussion

The SWCNTs–PVA functions as an SA that preferentially transmits high power and promotes the formation of a pulse from noise. The saturable absorption feature of the SA is independent of the polarization of light because of the random orientations of SWCNTs. Stable self-starting mode-locking begins when the pump power reaches 35.2 mW. Fig. 3 shows the output spectra of the proposed EDFL at four different pumping powers: 35.2, 44.3, 56.4 and 71.0 mW. At the threshold pump power of 35.2 mW, the laser exhibits a broad spectrum with steep spectral edge and two wavelength peaks (which look like horns). This is attributed to the dissipative soliton resonance effect which clamps the peak intensity of the laser and thus broadens the pulse width. The signal to noise ratio of the spectrum is measured at around 23.5 dB. As the pump power increases to 44.3 mW the spectrum bandwidth slightly shrinks but the signal to noise ratio improves