Optical Fiber Technology 19 (2013) 200–205

Contents lists available at SciVerse ScienceDirect

Optical Fiber Technology

www.elsevier.com/locate/yofte

Regular Articles

The generation of dissipative solitons in an all-fiber passively mode-locked laser based on semiconduct type of carbon nanotubes absorber

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ARTICLE INFO

Article history:
Received 19 June 2012
Revised 15 January 2013
Available online 7 March 2013

Keywords:
Semiconductor
Carbon nanotubes
Absorber
Fiber laser
Mode locking

ABSTRACT

We report theoretically and experimentally on the formation and compensation of dissipative soliton (DS) in an all-normal dispersion fiber laser mode locked with semiconductor type of carbon nanotubes (CNTs) absorber fabricated by vertical evaporation method. The pulses with bandwidth of 2.2 nm and duration of 11.7 ps are obtained at 1051 nm. The DS is linearly chirped and can be compressed to 1.8 ps by a grating pair. By this method the carbon nanotubes absorbers is can be mass produced cost effectively and easier to control the absorber parameters, e.g. initial transmission of the absorber, therefore this method is more suitable to be industrialized.

1. Introduction

Passively mode-locked all-fiber lasers have been extensively investigated because of their compactness, flexibility, and low cost [1–4]. Various mode locking techniques including nonlinear optical loop mirror (NOLM) [5], nonlinear polarization rotation (NPR) [6–9] and passively mode locking with saturable absorbers (SAs) [10–18] have been used to generate ultrashort pulses. As for a NOLM mode-locked fiber laser, a long fiber is needed to provide enough nonlinear phase shifts. The NPR technique is sensitive to environment, such as vibration and temperature, which severely limited its use in practical applications. The passive saturable absorbers such as semiconductor saturable mirrors (SESAMs) [10], carbon nanotubes (CNTs) [11–15], and graphene [16–18] are widely utilized for passive mode locking because they are indifferent to polarization depending mode locking. However, SESAMs suffer from high costs, complex fabrication, narrow wavelength band, low damage threshold and long recovery time for ultra-short pulse generation. On the contrary, CNTs and graphene absorbers have some advantages such as low-cost raw material, simple fabrication technique, wide operational wavelength band, and short recovery time [12,17]. As far as now, CNTs absorbers have been fabricated by many techniques, such as absorber with CNT coated on a substrate [11,19], solution based CNT absorber [20], evanescent field interaction based CNT absorber [21], CNT absorber with directly grown on the fiber end [22] and so on. However, these methods have some drawbacks that made them not so suitable for industrial applications. CNT absorber based on a substrate generally is thick and hard, it cannot be attached on fiber tips and require bulky collimation setup to be integrated within the fiber system. For the solution based CNT absorber, it is difficult to find host solution with low optical loss and right reflective index to be fix into a hollow fiber. Liquid evaporation and CNT aggregation will also be other problem of the absorber. CNT absorber based on evanescent field require physical challenge of the optical fiber e.g. tapered the fiber or side polishing the fiber core, that will introduce extra optical losses and expensive. The CNT layer grown directly on the fiber end cannot easily control the thickness of CNT (initial transmission of the absorber) and CNT layer with high purity cannot be easily produced by this method, which will bring high non-saturable losses. Low-cost, high fabrication speed, high operation stability and parameters e.g. CNT concentration adjustability are very important industrial production of the absorbers. Vertical evaporation method is a very simple and cost effective way to fabricate CNT or graphene absorber based on a substrate [23–26] or absorber film [27,28]. Vertical evaporation method is a very simple way to fabricate CNT or graphene absorber based on a substrate [23–26] or absorber film [27,28]. In this paper, we fabricated

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1068-5200/$ - see front matter © 2013 Elsevier Inc. All rights reserved.
http://dx.doi.org/10.1016/j.yofte.2013.01.007

SWCNT/PVA composite absorber which is similar to that in Ref. [27]. Semiconductor type of SWCNT is chosen in this paper in order to reduce the non-saturable losses (metal type of SWCNTs does not play role in mode locking, while most SWCNTs material composed of semiconductor and metal type of SWCNTs). The concentration of the SWCNT is needed to be high to increase the saturable absorption because the modulation depth of the absorber need be higher in the high gain fiber lasers than that in solid-state lasers. All-normal dispersion mode locked fiber laser has been demonstrated using the CNT absorber. Pulse duration is estimated to be 11.7 ps. The pulse is linearly chirped and can be compressed by a grating pair to 1.8 ps. The average output power is 7.5 mW and was then amplified to 70 mW. Higher average output power could be obtained by using higher power amplification diode laser. This mode locked fiber laser can be used as the seed source for high power picosecond laser for most of the picosecond laser micro-processing applications.

2. Experimental setup

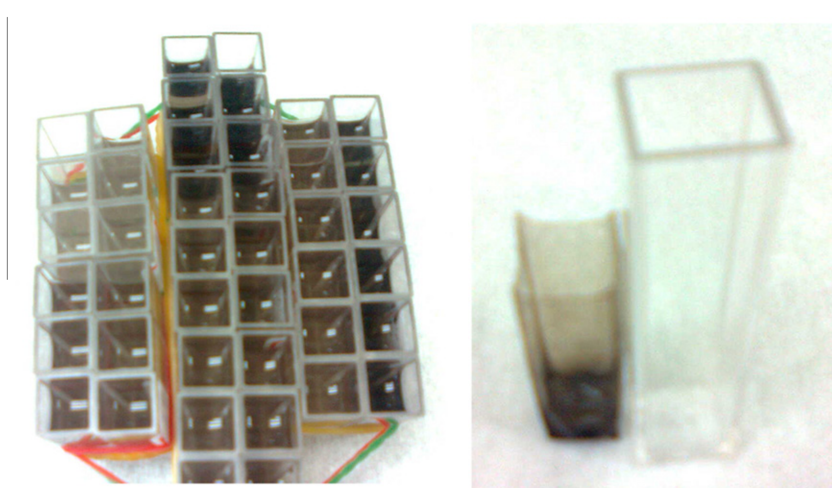
2.1. Device fabrication and characterizations

The SWCNTs are grown by the electric arc discharge technique. The chirality, the mean diameter, and the purity of the semiconductor type of SWCNT is (7, 6), 0.8 nm, and 77%, respectively. Firstly, 2.5 mg of SWCNT powder are poured into 10 ml 0.1% sodium dodecyl sulfate (SDS) aqueous solution used as a surfactant. In order to obtain SWCNT aqueous dispersion with high absorption, this solution is ultrasonically agitated for 10 h, and subsequently centrifuged to induce sedimentation of large SWCNT bundles. The upper portion of the centrifuged solution is decanted to a bottle. Some polyvinyl alcohol (PVA) powder is poured into the bottle and dissolved at 90 °C with ultrasonic agitation for 3 h. The SWCNT/PVA dispersion is poured into a polystyrene cell. Finally, the cell is evaporated in a 40 °C oven for 1 day. The wall and the bottom of the cell are coated with a thin plastic film because the PVA aqueous solution has strong viscosity to the polystyrene cell. When the cell is dry, the PVA film loses its viscosity and therefore can be easily stripped off by a tweezers. The SWCNT/PVA film on the cell wall has higher quality than that on the cell bottom so that the former can be used as an absorber for mode locking. The procedure to fabricate the absorber is very simple and suitable to be mass produced. The SWCNT/PVA film on the cell wall has higher quality than that on the cell bottom for some reasons: One, much impurity was deposited on the bottom because of gravity force. Two, the final step of evaporation in the solution will leave trace on the bottom. Three, the bottom of the cell can not be very smooth. Forth, all the residual PVA/SWCNT are deposited on the bottom without selection. Fig. 1 shows the diagram for the fabrication of SWCNT absorber.

The properties of the SWCNT/PVA absorber can be modified by adjusting the quantity and ratio of the SWCNT and PVA in the aqueous solution. The increase of the content of the SWCNT in the solution will lead to the increase of saturable absorption depth and non-saturable losses of the SWCNT absorber. The increase of the content of PVA in the solution will made the film harder and thicker. Super soft and thin film under pressure may fracture easily, whereas if it is too hard and thick, it cannot be attached to the surface of the flange connected to the fiber without air gap in between. Therefore, both the quantity and ratio of SWCNT and PVA need to be optimized with respect to the mechanical and optical properties accordingly.

2.2. Laser setup

The experimental system is schematically shown in Fig. 2. It consists of three parts: a laser oscillator, an amplifier, and a pulse compressor. The laser oscillator comprises a 980/1053 nm wavelength-division-multiplexed (WDM) coupler, a 0.7-m long YDF with absorption coefficient of 179 dB/m at 976 nm, a polarization insensitive isolator (PI-ISO) with bandwidth of 10 nm at 1053 nm center wavelength, a fused optical coupler (OC) with 40% output, and a polarization controller (PC). The other fibers in the cavity are the standard single mode fiber (SMF) with a total length of 5.3 m. The dispersion parameters for YDF and SMF are about 20 ps^2/km and 22.1 ps^2/km at 1050 nm, respectively. The laser oscillator is pumped by a 976-nm single-mode laser diode (LD). The PI-ISO with a 10-nm filter and the PC are used to make the light propagate unidirectionally in the cavity and to adjust the linear cavity birefringence, respectively. The 2-mm^2 SWCNT absorber is sandwiched between two fiber ferrules inside a physical contact ferrule connector. The output properties of the laser oscillator are monitored by an optical spectrum analyzer, a digital storage oscilloscope, a radio-frequency (RF) analyzer, a power meter, and a commercial autocorrelator. Output pulses are amplified by an



(a) (b)

Fig. 1. The diagram for the fabrication of SWCNT absorber (a) the polystyrene cell filled with SWCNT/PVA dispersion for the growth of absorber and (b) the left is SWCNT/PVA film and the right is the polystyrene cell.