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Photodeposition of SWCNTs onto the optical fiber end to assemble a Q-switched Er^{3+}-doped fiber laser

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ABSTRACT

An experimental study on optical pulses generation using single-wall carbon nanotubes as a saturable absorbers in an Er^{3+}-doped fiber laser is reported. The saturable absorber was made by the photodeposition technique to place single-wall carbon nanotubes onto an optical fiber end. This technique consists of light laser provided by an Er^{3+}-doped fiber amplifier and single-wall carbon nanotubes suspended in an aqueous solution. Using a fiber splice tube, the optical fiber with the single-wall carbon nanotubes is placed in the Er^{3+}-doped fiber laser cavity. The nonlinear absorption of the saturable absorber was characterized by P-scan technique using a high gain pulsed Er^{3+}-doped fiber amplifier. The results demonstrated that is possible to obtain optical pulses generation by using the single-wall carbon nanotubes as saturable absorber. The pulses duration are from 8.5 to 18 μs with a repetition rate around of 16–19.5 kHz. The nonlinear absorption of the single-wall carbon nanotubes photodeposited onto an optical fiber end is approximately -5.25×10^{-6} m/W.

1. Introduction

The carbon nanotubes have been widely investigated because of their physical and chemical properties, since they were obtained in 1991 [1]. These nanotubes are commonly classified into two categories: single-walled carbon nanotubes (SWCNTs) and multi-walled carbon nanotubes (MWCNTs) [2]. In particular, SWCNTs have important features such as polarization insensitivity, high optical damage thresholds, very quick recovery times (< 1 ps), chemical stability, and the ability to operate in transmission or reflection, as well as bidirectional propagation [3,4]. In addition, these exhibit great optical nonlinear effects in the near-infrared region (1.2 μm – 2.0 μm) [5,6]. These effects are ideal for producing photonic devices such as optical switches, pulse compressors, noise filters, optical limiters, among others. Consequently, SWCNTs are widely used as saturables absorbers in optical fiber lasers to generate giant pulses in the optical communications range (1.55 μm).

Passively Q-switched Er^{3+}-doped fiber lasers have been intensely investigated to produce short and high energy pulses using different types of saturable absorbers, such as transition metal doped crystals [7] or semiconductor saturable absorber mirrors (SESAMs) [8]. However, these saturable absorbers are complex and expensive to be fabricated. On the other hand, saturables absorbers based on SWCNTs are inexpensive and their implementation is relatively simple.

In this context, the carbon nanotubes have been reported in different configurations as saturable absorber in cavity fiber lasers. The typical configurations of SAINTs (SAINT, Saturable Absorber Incorporating Carbon Nanotubes) are: i) transmission (T-SAINT), that involves a thin layer of SWCNTs between two quartz substrates; ii) reflective (R-SAINT), created by a thin layer coated on a high reflective mirror [9]; iii) D-shape (D-SAINT), which is very complicated to made because it is necessary to remove a section of the cladding and fill it with SWCNTs [10,11]; and iv) ferrule (F-SAINT), it is based on a construction on which a substrate with SWCNTs are placed between two optical fibers using lenses or by photodeposition technique [12,13]. Otherwise, it has been reported that it is possible to make saturable absorbers by the immobilization of SWCNTs on an optical fiber end using laser light and SWCNTs suspended in solution. In this case it has been assuming that the mechanisms responsible of this phenomenon are the optical tweezers effect, convection currents or thermophoresis

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[13]. Recently, it was demonstrated that convection currents are the phenomena involve in the photodeposition process of zinc nanoparticles [14].

In this work, a Q-switched Er^{3+}-doped fiber laser (EDFL) using SWCNTs onto an optical fiber end is reported. The SWCNTs are deposited onto the optical fiber end by photodeposition technique using an Er^{3+}-doped fiber amplifier (EDFA) as a light source. By using SWCNTs as a saturable absorber in an EDFL cavity is obtained optical pulses with a duration between 8.9 µs and 18.1 µs with a pulse repetition rate between 15.9 kHz and 19.5 kHz. The nonlinear absorption of SWCNTs adhered on the optical fiber end are characterized using a high intensity pulsed source, the nonlinear absorption coefficient measured is -5.25×10^{-6} m/W.

2. Photodeposition technique

The photodeposition technique has been used to deposit nanoparticles onto an optical fiber end, which is well-known and has been reported previously [14–16]. With this technique is possible to choose the maximum size of nanoparticles adhered onto the optical fiber end by means of the laser power. Furthermore, the amount of nanoparticles depends on laser power and the time of the optical fiber submerged into the aqueous solution.

In this case, both SWCNTs suspended in isopropyl alcohol and an EDFA as source light are used in the photodeposition process. The pumping source for the EDFA is a semiconductor laser at $\lambda = 980$ nm with a maximum power of 140 mW. The pumping power is coupled into the EDFA by means of a 980/1550-nm wavelength division multiplexing (WDM) coupler. The gain fiber is 10-m-long single mode Er^{3+}-doped fiber (EDF) with an erbium concentration of 1000 ppm (see Fig. 1). In order to be sure that there is a unidirectional operation, an optical fiber isolator is placed between two polarization controllers (PC). Finally, a single-mode fiber (SMF) prepared by removing the coating and its cleaving is placed into the aqueous solution.

It was used SWCNTs manufactured by catalytic CVD, with outside diameter: 1–2 nm, inside diameter: 0.6–1.6 nm and length: 5–20 µm (SkySpring Nanomaterials, INC). In Fig. 2, the Raman spectrum in nanotubes correspond to the characteristics previously reported [17,18].

The solution is prepared by mixing 8 cc of isopropyl alcohol and 2.6 mg of SWCNTs. By an ultrasonic bath for 10–15 min is homogenized. When the pumping power is turn on the SWCNTs are adhered to the optical fiber end, as it is shown in Fig. 3.

Through a scanning electron microscope (SEM) a micrograph of SWCNTs photodeposited on the optical fiber end with an optical power of 30 mW at a time less than 30 min is obtained, see Fig. 3. Inset in Fig. 3 shows that the thickness of the SWCNTs layer is approximately 900 nm.

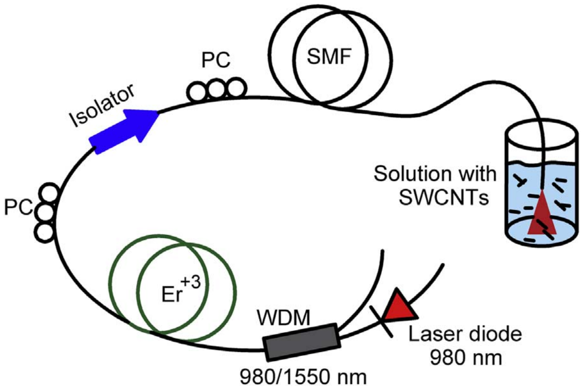

Fig. 1. Experimental setup to photodeposit SWCNTs onto optical fiber end.

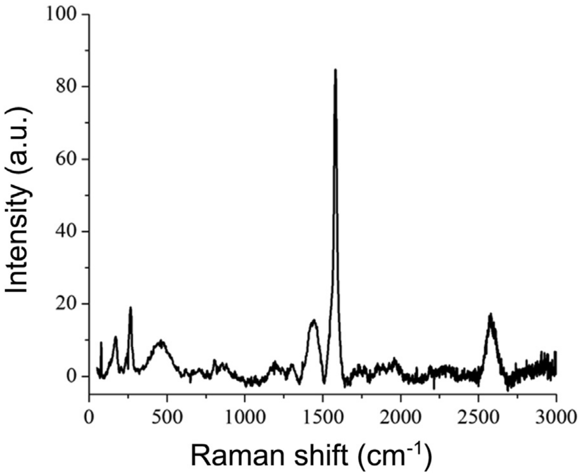

Fig. 2. Raman spectrum of SWCNTs deposited onto optical fiber end.

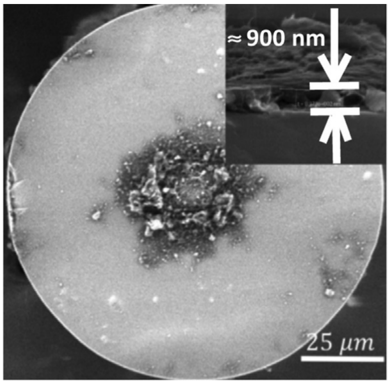

Fig. 3. SEM image of SWCNTs deposited on the optical fiber end by photodeposition technique.

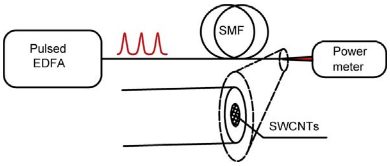

Fig. 4. Experimental setup to measure nonlinear transmission of SWCNTs photodeposited onto the optical fiber end.

3. Nonlinear characterization

Fig. 4 shown the experimental setup for nonlinear characterization of the saturable absorber. The nonlinear absorption coefficient of the SWCNTs deposited on the optical fiber end is characterized by using a high power pulsed Er^{3+}-doped fiber amplifier (HP-EDFA) reported in [16].

The transmission obtained can be expressed as a function of the intensity using the Beer-Lambert law [19]:

$$T = \exp[-\alpha(I)L], \quad (1)$$

where $\alpha(I)$ is the absorption coefficient, L is the sample length, and I is the intensity. We considered a saturation model and therefore, we used a hyperbolic approximation [20,21]:

$$\alpha(I) = \frac{\alpha_s I}{1 + I/I_{sat}} + \alpha_{ns}, \quad (2)$$

where α_s and α_{ns} are the saturable and non-saturable absorption, respectively, I_{sat} the saturation intensity is defined as the intensity when the transmission has reached 50% of depth of modulation.

By combining Eqs. (1) and (2) we obtained the transmittance

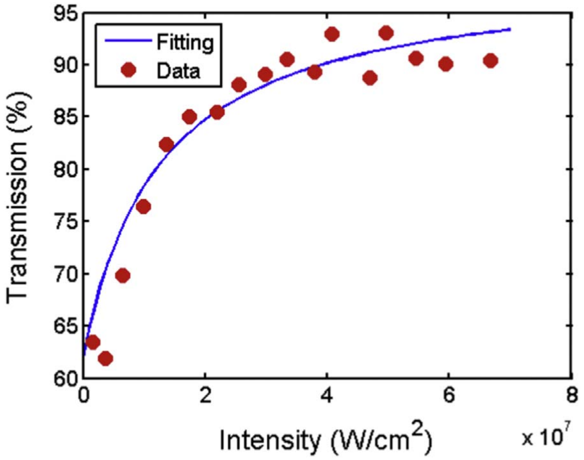

Fig. 5. Transmission as a function of the peak intensity of SWCNTs photodeposited onto the optical fiber.

expression:

$$T = \exp\left[-\left(\frac{\alpha_s I}{1 + I/I_{sat}} + \alpha_{ns}\right)L\right] \tag{3}$$

The experimental nonlinear transmission curve is obtained applying intensities of up to 7×10^7 W/cm^2 from the HP-EDFA on the SWCNTs deposited on the optical fiber. The results are shown in Fig. 5.

The curve fitting in Fig. 5 is obtained using the Eq. (3), with $\alpha_s = -5.25 \times 10^{-6}$ m/W, $\alpha_{ns} = 5.32 \times 10^3$ cm^{-1} and $I_{sat} = 9.91 \times 10^6$ W/cm^2. The non-saturable losses are approximately 7%.

When the SWCNTs are deposited in the optical fiber end the transmission losses measured is stated at 3 dB. However, we consider that when the nonlinear characterization was achieved, the radiation pressure from the HP-EDFA has detached some nanoparticles from the optical fiber end. Therefore, the transmission increased and the modulation depth measure begin at around 60%.

4. Q-switched Er^{3+}-doped fiber laser

The optical fiber laser consists of an Er^3-doped cavity in a ring configuration. In this case, an output coupler 90/10 is used in the EDFA showed in Fig. 1. Then 10% of the radiation intensity that comes out for the laser cavity is measured; whereas 90% is used as feedback. The SWCNTs photodeposited onto the optical fiber end are placed as a saturable absorber in the cavity laser. To align the ends of the optical fibers a fiber splice tube is used, as shown in Fig. 6. The output coupler is connected to an ultrafast photodetector with a bandwidth of 1.2 GHz, which is connected to a digital oscilloscope to present and analyze the temporal emission.

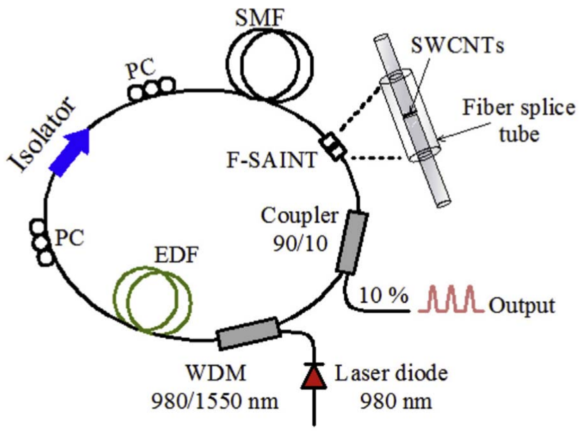

Fig. 6. Erbium-doped fiber ring laser.

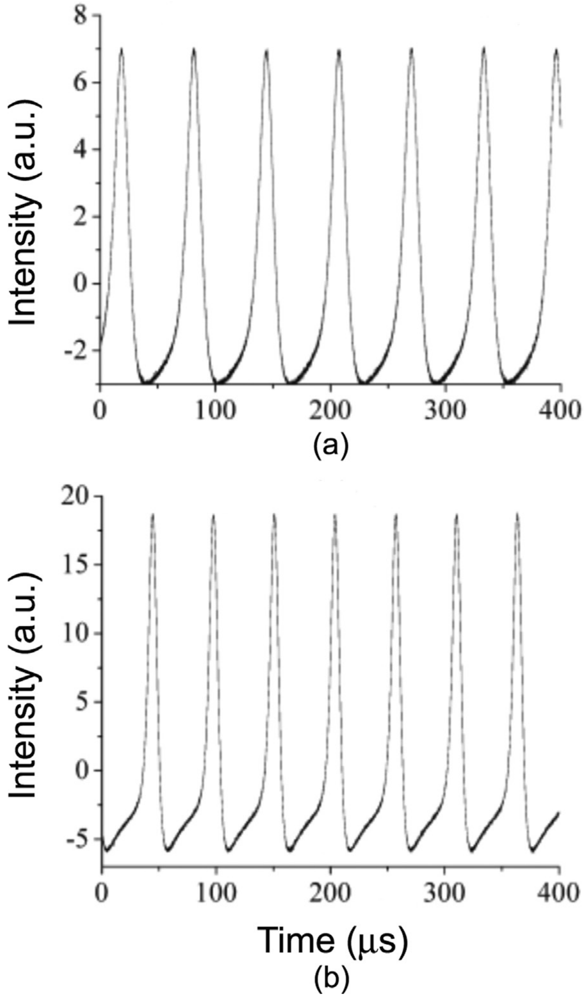

Fig. 7. Typical traces of Q-switched laser operation for pump power of (a) 49.2 mW and (b) 67.5 mW.

In this case, it is observed that Q-switched operation starts at 46.3 mW pump power. The typical oscilloscope traces of pulses train for a laser output at 49.2 mW and 67.5 mW pump power are showed in Fig. 7.

The optical spectrum measured in Q-switching state is presented in Fig. 8, where the central emission wavelength was at 1597 nm.

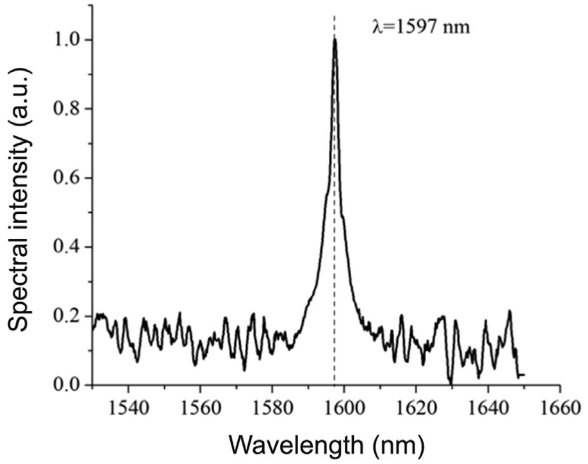

Fig. 8. Output spectrum of the Erbium-doped fiber ring laser in Q-switching state.

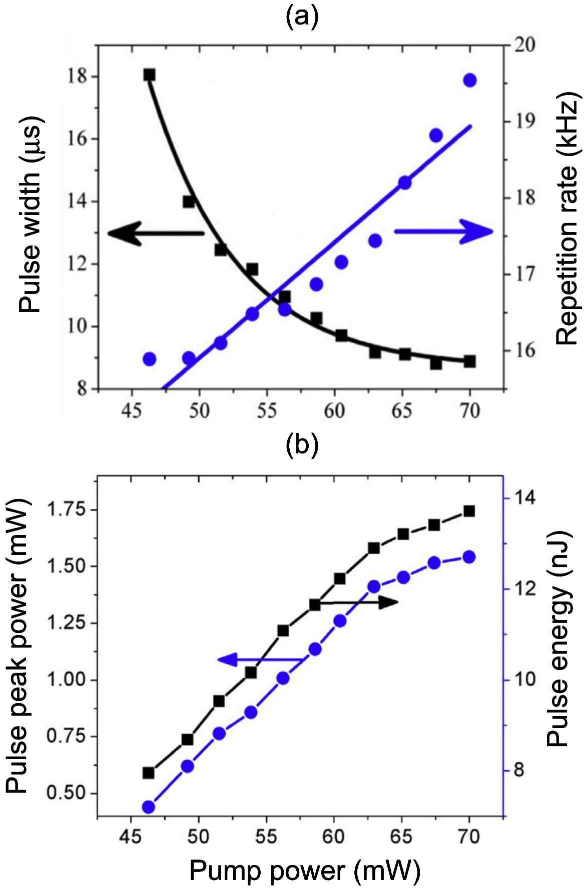

Fig. 9. (a) Pulse duration and repetition rate as a function of the pump power, and (b) pulse peak power and energy as a function of the pump power.

Fig. 9 shown that by increasing the pump power from 46.3mW to 70 mW the repetition rate, the pulse peak power as well as the pulse energy are higher, and the pulse duration is shorter from 18 µs to 8.5 µs. Then repetition rate is pump dependent, a typical behavior of a self-started Q-switching [22].

Therefore, the results of this experimental work confirm that the Er^{+3}-doped fiber laser is working in a Q-switched state, with a lower pump threshold, by using SWCNTs photodeposited onto the optical fiber end as a saturable absorber into the laser cavity. The photodeposition technique used in this work to make the saturable absorber is easier and inexpensive. Meanwhile, the nonlinear characterization by means of the P-scan technique is relatively simple.

5. Conclusions

In this work, a photodeposition technique to adhere SWCNTs onto the optical fiber end has been used, which are applied as a saturable absorber in an Er^{+3}.-doped fiber laser. The optical pulse duration can be tuned from 8.5 to 18 µs with its repetition frequency from 16 to 19.5 kHz with the pump power from 46.3 up to 70 mW. Furthermore, the nonlinear absorption of -5.25×10^{-6} m/W for the SWCNTs adhered on the optical fiber end has been measured. These results could be use for applications in the fields of telecommunications, laser processing or sensing.

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