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Generation of ultra-fast laser pulses using nanotube mode-lockers

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We report a simple way to fabricate a high optical quality single wall carbon nanotubes (SWNTs) polyvinyl alcohol (PVA) composite. The composites demonstrate strong saturable absorption at ~1.5 μm, the spectral range for optical communications. These are used as mode-lockers in a fiber laser. We achieve ~713 fs pulse generation and up to 8 mW output power.

1 Introduction

The non-linear optical properties of SWNTs are at the centre of an expanding area of research. SWNTs are good saturable absorbers with an ultrafast recovery time, i.e. they are pass-high filters for light, becoming transparent for sufficiently high incident power [1, 2]. This makes them ideal components for a wide range of photonic devices, such as all-optical switches, pulse compressors, noise regenerative filters, etc. Many key applications of carbon nanotubes in electronic devices require individual tubes with given chirality for their optimum performance. However, precise chirality control is not necessary if we want to exploit their electronic properties to build ultra-fast optoelectronic devices. The main requirement is to control the average diameter distribution to match the wavelength of interest. Furthermore SWNTs can be easily processed in film or polymer composites. They also have very good radiation and thermal stability. These makes them very competitive when compared to existing passive mode-locking technology, based on semiconductor saturable absorber mirrors, which are molecular beam epitaxy grown multiple quantum wells requiring expensive packaging [3].

Here we report the generation of ultrashort laser pulses in erbium doped fiber lasers by using SWNTs-PVA saturable absorber films. The SWNTs-PVA composite does not show laser or environmental damage after continuous operation in the laser cavity.

2 Experimental

We use purified SWNTs prepared by laser ablation as starting material. The synthesis is described in Ref. [4]. We use Ar as flow gas, 1 atom % Ni and Co as catalyst. The diameter distribution can be varied by changing the oven temperature. Figure 1 shows the absorptions spectra taken from the free-standing samples synthesised at 5 different oven temperatures. The as-prepared soot is further purified by a procedure described in Ref. [5] by using dimethylformamide to wash out fullerenes, amorphous carbon and

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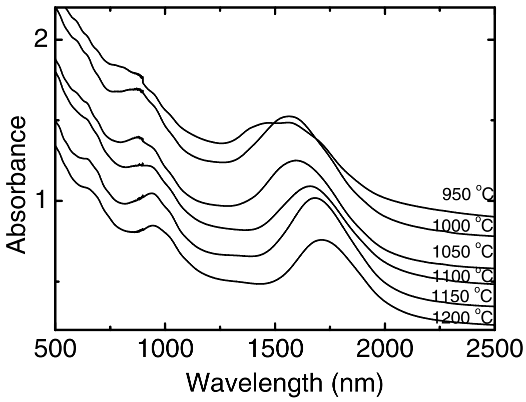

Fig. 1 Optical absorbance of SWNTs prepared at different oven temperature.

some of the metal content. 0.4 weight % SWNTs are dispersed in water together with 5 weight % sodium dodecylbenzene sulphonate (SDBS) as a surfactant. This is followed by ultra-sonication for 4 hours at 200 W, using a commercially available ultrasonic processor (Bioruptor, Diagenode SA). The resulting SWNTs solution is then filtered through a glass microfibre filter with glass fiber diameter 1 µm, to remove large bundles. Next, the SWNTs solution is mixed with 20% PVA (13000–23000 average molecular weight) aqueous solution and ultrasonicated again for 40 minutes at 200 W. This is then placed on a Petri dish to evaporate water. This procedure gives free-standing SWNTs-PVA films with a thickness of ~50 µm. The optical properties of the composites are studied by UV-VIS-NIR spectrophotometry and micro-Raman spectroscopy at different excitation wavelengths. SWNTs-based mode-lockers are fabricated by placing the SWNTs-PVA composites between two fiber ends in pig-tailed FC/PC connectors (Fig. 2). An index matching gel is applied to both fiber ends to minimize the insertion losses in the FC/PC connector.

The laser setup is shown schematically in Fig. 3. The laser cavity is constructed by using an erbium doped fiber amplifier (EDFA). The other cavity components are the mode-locker, a fiber polarization controller (PC), an isolator and 0.4 m of dispersion compensated fiber (DCF). We use one port of the 50/50 coupler to have a feed-back into the cavity, while the other is used to study the cavity repetition rate, autocorrelation trace, pulse spectrum and output power. The EDFA consists of 40 meters of erbium doped fiber (EDF) pumped by a semiconductor diode laser at 980 nm. This results in the excitation of the Er^{3+} high-energy excited states, followed by a non-radiative recombination to lower-energy excited states [6]. The subsequent radiative recombination from these levels to ground state gives an emission at 1530 nm. The laser feedback is created using the 50/50 optical fiber coupler to obtain gain. The laser beam returns to the EDFA trough a wavelength division multiplexer (WDM), which transmits light at 1530 and 980 nm in a single fiber. Thus, the stored pumping energy of the low-energy excited state is used to amplify the signal through stimulated emission. When the pumping power exceeds the cw threshold, cw lasing is observed from the second port of the 50/50 coupler.

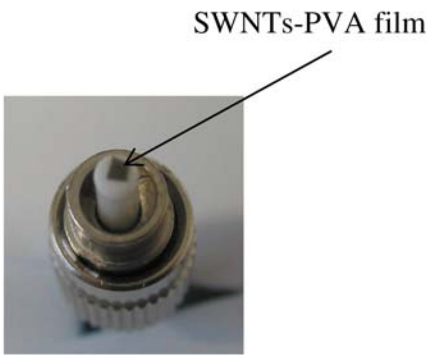

Fig. 2 (online colour at: www.pss-b.com) FC fiber connector with SWNTs-PVA film attached on the fiber surface.

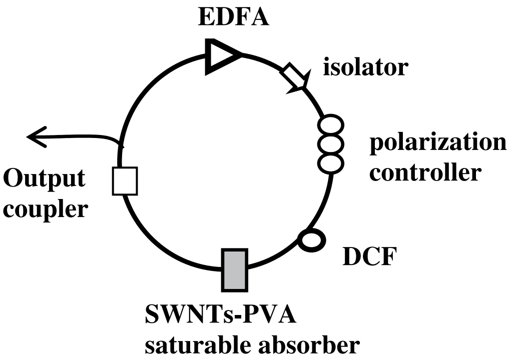

Fig. 3 Sketch of EDF laser with SWNTs based mode-locker.

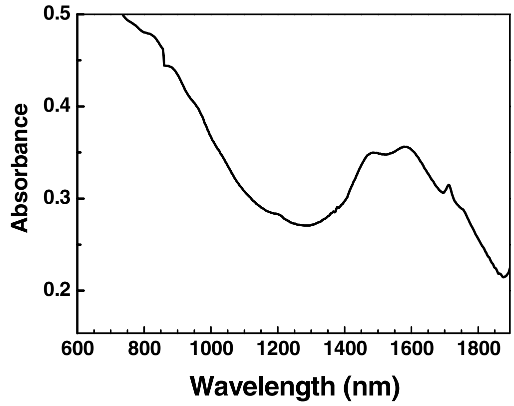

Fig. 4 Absorbance of the SWNTs-PVA film.

3 Results and discussion

To design an efficient SWNTs saturable absorber, i.e. to achieve the maximum amount of saturable losses (maximum modulation depth), it is important to be as close as possible to resonance [7]. The absorption band of the sample should match the laser cavity wavelength (1550 nm). We thus use SWNTs with a diameter distribution between 1.1 and 1.3 nm, as indicated by Raman spectroscopy. The corresponding SWNTs-PVA composite has a broad absorption band (FWHM ≈ 200 nm) centred at ~1530 nm (Fig. 4). It should be noted that the saturable absorption properties of the composites can be affected by several other factors, such as scattering losses on bundles, non-saturable absorbance on impurities, polymer matrix and surfactant [2]. These are processing issues and are optimised by a trial and error.

To achieve pulsed lasing from the cw regime, we place the pig-tailed SWNTs-PVA mode-locker in the cavity. This gives stable mode-locking with a fundamental repetition rate ~5 MHz and output power between 3 and 9 dBm (2 and 8 mW). Figure 5 plots the output pulse spectrum. The sharp intensity decrease in the long-wave spectral range is due to the limitation of our EDFA output spectrum (EDFA curve, Fig. 5). The main band, responsible for short pulse formation, is broadened around ~1560 nm. However, we observe a spike about 1562 nm, which is more pronounced under low pumping conditions.

This is probably caused by a residual cw emission in the cavity, because the intra cavity power is not enough to fully saturate our saturable absorber. This is confirmed by the spectrum measured for the

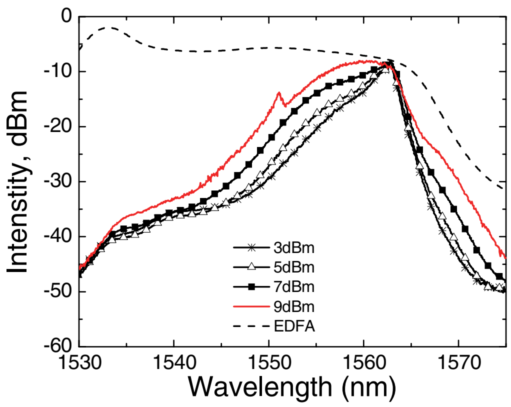

Fig. 5 (online colour at: www.pss-b.com) Output optical pulse spectrum.

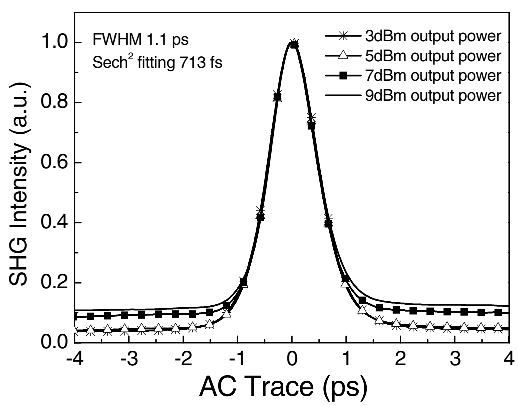

Fig. 6 SHG autocorrelation trace.

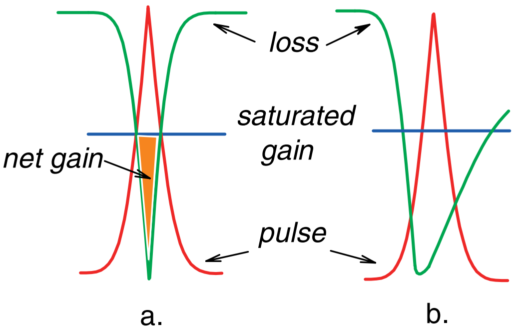

Fig. 7 (online colour at: www.pss-b.com) Mode-locking mechanisms with (a) ultrafast saturable absorber, (b) soliton mode-locking.

highest output power (9 dBm), which does not have this spike. However, for the highest output power we observe two sidebands about 1551 and 1570 nm in symmetric positions with respect to the main band. These can be assigned to chirped solitons [6]. Soliton pulses lose part of their energy passing through the output coupler, but then regain it during the cavity round trip. The soliton adjusts to these perturbations by forming dispersive waves, which appear as spectral sidebands [6].

The pulse width of the laser is measured using second harmonic generation (SHG) auto-correlation [8]. The pulses in Fig. 6 are fitted with a sech^2 autocorrelation function, with a full width at half maximum (FWHM) of 1.1 ps. To get the real pulse width, the autocorrelation width needs to be divided by the decorrelation factor for the sech^2 (1.54) [8]. This gives a pulse width of ~713 fs. The pedestal in the autocorrelation data is an evidence of minor noise in the cavity. The intercavity noise is mostly caused by insertion losses and non-saturable absorbance of polymer matrix.

The mechanism of pulse formation can be understood as follows [9]. The saturable absorber works as a loss modulator when a short pulse circulates in the cavity (Fig. 7a). The peak intensity saturates the absorber more than the low intensity pulse wings. This produces an amplitude loss modulation with a frequency proportional to the cavity round trip. The pulse circulation in the cavity gives enough gain to overcome the losses induced by the absorber. As a result the net gain window has a duration equal to the absorber recovery time. The initial pulse formation can start from noise fluctuations in the laser cavity, when a high intensity spike significantly decreases its losses passing through the saturable absorber. It should be noted that it is possible to achieve pulses significantly shorter than the saturable absorber recovery time (Fig. 7b) [10]. In this case, soliton pulses form in the cavity as a balance between negative group velocity dispersion and self-phase-modulation. In this case the saturable absorber acts as starting loss mechanism for mode-locking and later on stabilizes the soliton.

Some demonstrations of SWNTs mode-lockers were previously reported [11–14]. In these works, SWNTs were deposited on quartz or directly on fiber ends [11, 12], or used in water solution [13], or polymer composites [14]. However, the lasers had limited output power range for single mode operation, as well as other undesired effects such as chirping, multi mode locking or Q-switching instability.

4 Conclusions

We demonstrated a 713 fs passively mode-locked laser with an output power up to 8 mW based on SWNTs-PVA saturable absorbers. The laser operation is stable at least for several hundred hours.

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