# Mode-locked fiber laser using an SU8/SWCNT saturable absorber

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We report the fabrication of a saturable absorber based on SU8 single wall carbon nanotube (SWCNT) composite material. Thin films with a controllable thickness can be fabricated using a simple and reliable process. These films can be inserted between two FC/APC connectors in order to have an inline saturable absorber. A passive mode-locked laser was built by interleaving the fiberized saturable absorber in an erbium-doped fiber (*L*-band) ring cavity laser. The laser produces 871 fs pulses with a repetition rate of 21.27 MHz and a maximum average power of 1 mW. © 2011 Optical Society of America

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Passively mode-locked fiber lasers have several applications in metrology, biomedicine, spectroscopy and signal processing. Recently, single wall carbon nanotubes (SWCNTs) have attracted considerable attention due to their optical nonlinearity [1], ultrafast recovery time [2], and high damage threshold [3]. A variety of configurations have been implemented in order to integrate a saturable absorber based on SWCNTs into an all-fiber laser such as fiber tapers [4], D-shaped fibers [5], direct deposition of SWCNTs on the tip of the fiber [6], and thin films either on free space [7] or between fiber connectors [8,9]. Among these methods, the use of thin films offers not only the simplest way to incorporate SWCNT in a fiber laser, but also a more consistent fabrication process. Different kinds of polymers have been used to fabricate reliable and reproducible films that contains SWCNTs such as polycarbonate (PC) [7], carboxymethyl cellulose (CMC) [10,11], polyvinylalcohol (PVA) [12], polymide [9], poly-methyl-methacrylate (PMMA) [13], polystyrene (PS) [13], and poly-3-hexylthiophene (P3HT) [14,15]. In order to choose a particular host polymer matrix, we have to take into account design parameters that are essential to the absorber's performance. The first is good dispersion of the SWCNTs to avoid formation of bundles that could deteriorate their optical properties. This is directly related to the polymer solvent as well as to the quantity of SWCNTs to be incorporated. Therefore, the choice of SWCNT film thickness and concentration also is essential for obtaining stable and short mode-locked laser operation [12,16]. In addition, we must also consider the mechanical and thermal properties of the polymer. Although the majority of composite films operate fairly well as saturable absorbers (SAs), most of them exhibit various drawbacks such as being unusual polymers (that are not widely used in photonic applications), requiring polishing of the surfaces, and having low glass-transition temperatures.

In this Letter, we present for the first time, to the best of the authors' knowledge, the fabrication of a composite material made of SU8 with SWCNTs and its application as an SA. A key feature of SU8 is that its glass-transition temperature is on the order of 210 °C, which is 100 °C higher than any other polymer used as an SA. The SU8 material has also the advantage that is a well-known and inexpensive material employed for microfabrication. Additionally, since SU8 is a photosensitive material, its potential use for integrated waveguide devices provides a nice ground for their study. The fabrication process of the SU8/SWCNT films requires few and very simple steps to achieve well-dispersed SWCNTs, and the film thickness can be accurately controlled. We demonstrate a passively mode-locked fiber laser using the developed SU8/SWCNT film that generates pulses with durations of 871 fs and an average power of 1 mW at a repetition rate of 22.38 MHz.

The SWCNTs (synthesized by a high-pressure CO process, HiPCO) were purchased from the company Unidym. It is well known that SWCNT energy bandgaps vary in inverse proportion to the nanotube diameter [17]. In this work, we selected a range of tube diameters from 0.8 to 1.2 nm because they correspond to a bandgap of around 1550 nm. The composite films were fabricated as follows. First, SWCNTs were dispersed in cyclopentanone (which is the base solvent for SU8) and the suspension was sonicated for 30 min. After the nanotubes were fully dispersed, SU8-2075 was added slowly to the solution and the new mixture was placed in the ultrasonication bath and then in the stirring machine for 2 h and 3 h, respectively. The mixture of SU8-2075 and cyclopentanone was made by using 4 ml and 1 ml, respectively. The quantity of SWCNTs was calculated to have a concentration of 0.125 wt.%, which has been shown to be an ideal concentration when dealing with thin films of composite materials containing SWCNT [16]. In order to fabricate thin films of the SU8/SWCNT composite, we assembled a glass cell whose walls had been covered with polydimethylsiloxane (PDMS). The PDMS base and curing solution were mixed and spin coated on square glass slides to achieve a thin and uniform PDMS film. After coating the PDMS, it was cured by heating the glass slides on a

 

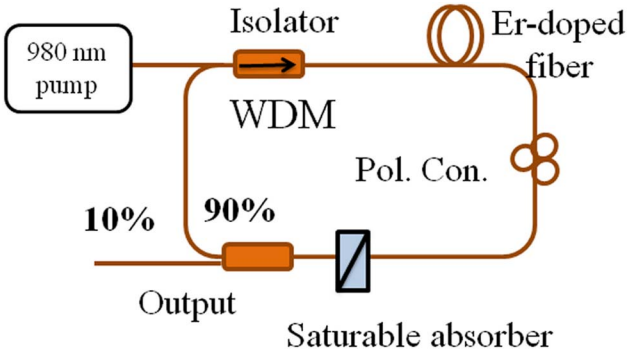


Fig. 1. (Color online) Schematic of the passively mode-locked fiber laser, developed using a SU8-2075/SWCNT film between two connectors.

hot plate at 100 °C for 1 h. The PDMS material on the glass allows the cured composite material to be peeled off very easily without a complex procedure. The SU8-2075/SWCNT solution was poured into the cell and the solution was cured according to the specification of the SU8-2075 polymer, taking into account that the film's thickness was 100 $\mu$m. We should highlight that the cell thickness can be easily controlled by changing the spacer thickness. After curing, a small piece of the film was carefully cut and placed between two FC/APC connectors in order to have an inline saturable absorber. Index matching liquid was not used because the FC/APC connectors eliminate undesired reflections. The linear transmission of the SU8-2075/SWCNT film at 1550 nm was about 67.5%. This corresponds to an absorption of 29% from the composite, and the remaining 3.5% loss is due to the connectors.

A passively mode-locked fiber laser was developed using a film of SU8/SWCNT for the SA, as shown in Fig. 1. The laser consists of approximately 3 m of erbium-doped fiber (EDF) that was pumped by a laser diode operating at 980 nm via a 980/1550 WDM fiber coupler. The peak absorption of EDF was 94.59 dB at 1530 nm. The WDM used had an isolator to ensure unidirectional operation. A polarization controller (PC) was included in the cavity not only to optimize the spectral width, but also to maintain a fixed polarization state in the fiber laser cavity. Detuning the intracavity polarization controller helps to achieve stable passive mode-locking. The output coupling ratio of the laser cavity was 10%. After amplification, the optical spectrum and second harmonic generation (SHG) autocorrelation were measured. At the same time, the pulse train and radio frequency spectrum were measured using a sampling scope and RF spectrum analyzer using a fast photodiode.

Before attempting to observe pulsed operation due to the SU8/SWCNT SA, the ring laser was first operated without the composite film. As expected, continuous wave (CW) operation was achieved for any pumping power. We also modified the PC at different pumping levels, and there was no indication of nonlinear polarization rotation mode-locking, as there is no polarizing element in the laser cavity. After the SU8/SWCNT SA was placed in the laser, a pulse train was attained above a threshold power of 36 mW. The minimum temporal pulse width and the time-bandwidth product were obtained at a pump power of 88 mW. The optical spectrum and SHG autocorrelation trace of the laser output were measured for the optimal pump power as shown in Figs. 2(a) and 2(b). The mode-locked laser's central wavelength was 1572.04 nm with a FWHM of 3.26 nm, as seen in Fig. 2(a). The FWHM temporal duration of the autocorrelation trace was 1.536 ps, as shown in Fig. 2(b), corresponding to a deconvolved pulse duration of 871 fs, assuming a sech squared pulse shape. The resulting time-bandwidth product was 0.344, which is close to the transform-limited value for sech squared pulse shape [18]. We should mention that dispersion was not compensated, which could provide shorter pulses. In addition, since the SWCNTs are randomly distributed within the polymer matrix, there is a slight polarization dependence on the thin film. Thus, placing the PC at the maximum absorption helps to obtain stable pulses.

The laser repetition rate was measured to be 21.27 MHz, as shown in Fig. 3. This value corresponds to a laser cavity length of about 9.4 m. The maximum average output power obtained from this configuration was 1 mW. An estimated intracavity power of 9.542 dBm is obtained, which is between 2 [6,7,9,14] to 9 [8,13,15] times higher than several mode-locked lasers using SWCNT thin-film composites. We should also note that the laser could be

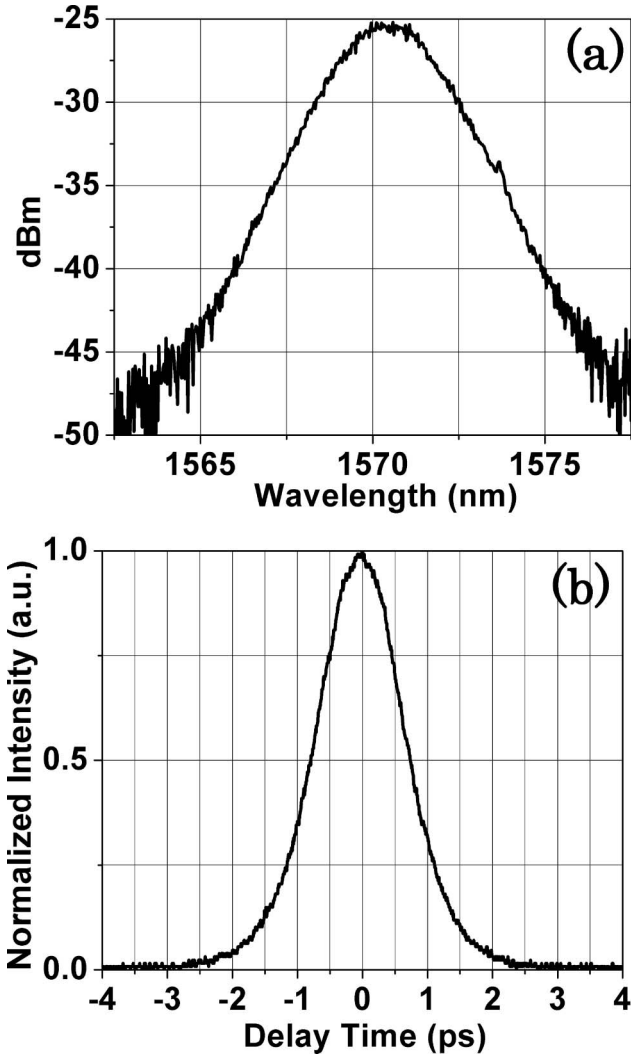


Fig. 2. (a) Optical spectrum of the pulse, (b) autocorrelation trace of the mode-locked pulse.

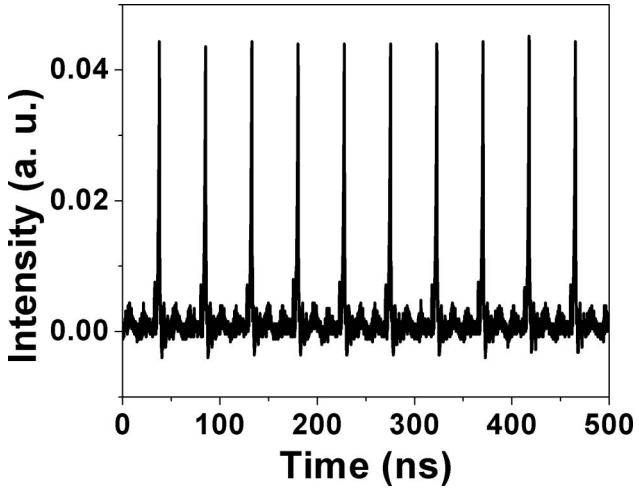


Fig. 3. Sampling scope trace of the mode-locked fiber laser output (photodetector bandwidth = 15 GHz).

operated at our maximum pump power of 115 mW without any degradation of the SU8/SWCNT composite. In addition, the average output power could easily be increased to 5 mW by using a 3 dB output coupler. This not only provides a higher output power, but also lowers the intracavity power, which in principle should allow a higher power operation. Because of the simplicity of the film fabrication process, we also tested different film thicknesses. In the case of films thinner than 100 $\mu$m, the absorption was too low to achieve stable single-pulse operation, and multiple pulse operation was observed. When the film thickness was increased, a higher modulation depth is expected, which could in principle reduce the pulse width duration; this was experimentally confirmed for films slightly thicker than 100 $\mu$m. However, as the thickness was increased, the losses due to the connectors containing the film were too high to achieve pulsed laser operation with the available pumping power. A higher absorption can also be obtained by increasing the SWCNT concentration. However, increasing the SWCNT concentration gives rise to the formation of bundles and potential damage to the film at low pumping powers. Based on these results, shorter pulses should be feasible by increasing the film thickness without increasing the SWCNT concentration. This could be achievable using, for example, special fibers that would allow increased interaction lengths. In our current setup, the 100 $\mu$m film is the optimum thickness to achieve stable mode-locked operation. It is important to highlight that after the mode-locked laser is self-started at the optimum PC position, no further tuning of the PC is required to start the laser. The pulse train was stable during several hours of operation.

In summary, a saturable absorber material consisting of SU8 doped with SWCNT was demonstrated. SU8 is a well-known and inexpensive material and the composite is very simple and inexpensive to fabricate. Moreover, given the functionality of SU8 for integrated devices, we believe that this material could be very useful for the development of integrated nonlinear devices for different photonic applications. In the present report, a passive mode-locked fiber laser was developed using this film, achieving a pulse width of 871 fs that was generated at a repetition rate of 21.27 MHz, with a maximum average output power of 1 mW.

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