Fabrication of PDMS/SWCNT thin films as saturable absorbers

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Abstract. We present a novel technique to fabricate a saturable absorber thin film based on Polydimethylsiloxane doped with Single Wall Carbon Nanotubes. Using this film a passive mode-locked fiber laser in a standard ring cavity configuration was built by inserting the film between two angled connectors. Self-starting passively mode-locked laser operation was easily observed. The generated pulses have a width of 1.26 ps at a repetition rate of 22.7 MHz with an average power of 4.89 mW.

1. Introduction
Passive mode-locked fiber lasers involve self-amplitude modulation surrendered by a saturable absorber (SA) which is an optical device that introduces some loss to the intracavity laser radiation. This loss is relatively large for low intensities but significantly smaller for short pulses with high intensity [1]. These lasers can generate stable short pulses and they can be used in many different optical areas such as optical communication, microscopy, spectroscopy [2] and biomedical applications [3]. Since Single Wall Carbon Nanotubes (SWCNTs) exhibit an ultrafast recovery time [4] and high third-order optical nonlinearities [5], several designs to obtain a saturable absorbers have been implemented in order to incorporate the SWCNTs inside a laser cavity. The most used method relies on mixing the nanotubes with a polymer to fabricate a thin film composite that facilitates placing the film within the laser cavity [6-8]. Another method takes advantage of evanescent field interaction of propagating light with the SWCNTs [9,10]. Even though evanescent filed devices show good results, a stringent fabrication process should be carefully done to accomplish an adequate nonlinear interaction length. Moreover, all the techniques mentioned above require special equipment and materials to obtain nice pulses.

Here we report the fabrication of a thin film made of Polydimethylsiloxane (PDMS) doped with SWCNTs and its application as a saturable absorber. PDMS polymer is cheap, optically clear, inert, and our fabrication technique does not require expensive or especial equipment. On a previous work a tapered fiber configuration covered with PDMS doped with SWCNTs was implemented as a SA.
However, the taper fabrication presents problems with the reproducibility of the device [9]. This configuration also should be designed to optimize the nonlinear interaction length to avoid high nonlinearities and big group velocity dispersion values at the waist of the taper [11]. The fabrication of our PDMS/SWCNT composite requires few and simple steps to achieve not only well dispersed SWCNTs but also accurate film thickness. An all-fiber self-starting passive mode-locked laser was developed by means of this PDMS/SWCNT film, generating a stable pulse train at a repetition rate of 22.7 MHz. The pulses have a width of 1.26 ps and the maximum average optical power was 4.89 mW.

2. Fabrication of PDMS/SWCNT thin films

Since the energy band absorption of the SWCNTs varies inversely with the tube diameters [12], choosing the correct diameters that absorb in a specific wavelength is a very important issue. We chose the diameter of the SWCNTs from 0.8 to 1.2 nm which corresponds to a wavelength of 1550 nm. The SWCNTs were purchased from Unidym Company and they were synthesized by high-pressure CO (HiPCO) method.

![Diagram of thin film fabrication process](image)

**Figure 1.** Schematic of the thin film fabrication process: (a) Two acrylic layers and the spacer between them. (b) Lateral view of the cell filled with PDMS/SWCNTs.

The nonlinear absorption coefficient is reduced because SWCNTs tend to bundle when they are in polymers [5]. In order to avoid bundles of SWCNTs, first SWCNTs were added in chloroform and that suspension was sonicated by 30 minutes. Adding SWCNTs at a concentration of 0.125 wt% is an adequate amount to obtain well dispersed SWCNTs and also to observe stabilized shortened pulses [13]. Then, PDMS was poured into the solution and this new mixture was placed in the ultrasonication bath and the stirring machine for 2 hours and 3 hours, respectively. Twenty per cent of the solution weight is chloroform and eighty per cent of the solution weight is PDMS. After that, we add a ten per cent of the total solution weight of the curing agent for the PDMS.

Using the solution of PDMS doped with SWCNTs a film was fabricated as shown in Figure 1. A cell was constructed with two acrylic layers and the cell thickness depends on the spacers. These two acrylic layers help to peel-off the cured composite material since PDMS does not stick to them. The PDMS/SWCNT solution was poured into the cell and it was cured by heating the sample at 95 °C for one hour and then we let it rest for 24 hours. After that, the cell was separated to obtain a film whose thickness was equal to the thickness of the spacer. The thickness of the film was 192 μm and was chosen according to reference [13]. A small piece of the film (2 mm X 2 mm) was cut and placed between two FC/APC connectors in order to have a saturable absorber device. Index matching liquid
was not used because the FC/APC connectors suppress reflections. The linear transmission of the PDMS/SWCNT film at 1550 nm was about 65% (including connector loss).

3. Mode-locked fiber laser using PDMS/SWCNT film

A passive mode-locked fiber laser in a ring cavity configuration was constructed by using a PDMS/SWCNT film as a saturable absorber. A 3 m long erbium doped fiber (EDF) was used as the laser gain medium (peak absorption of EDF was 94.59 dB at 1530 nm) and a laser diode operating at 980 nm was the pump source via a 980/1550 WDM fiber coupler. An optical isolator was inside the WDM to ensure unidirectional operation in the laser cavity. The saturable absorber device was introduced in the fiber ring laser, as shown in Figure 2. Since the laser operation has a slight polarization dependence attributed to the random arrangement of the SWCNTs within the PDMS polymer matrix, a polarization controller (PC) was inserted in the laser cavity. Furthermore, by playing with the PC a stable passive mode-locking system could be achieved. Fifty per cent of the intracavity lasing light is coupled out as laser output while the remaining fifty per cent is launched back into the cavity as feedback. The output light signal can be analysed by setting an optical spectrum analyser and second-harmonic-generation-type autocorrelator. At the same time, the pulse train and the radio frequency signal were detected by using a photodiode.

![Figure 2. Schematic of the passively mode-locked fiber laser using a PDMS/SWCNT film between two connectors.](image)

The pump power was slowly increased until a stable pulse train is achieved immediately above a threshold power of 31 mW. The minimum pulse width and the minimum time-bandwidth product can be obtained at a pump power of 85.38 mW. At this pump power, the autocorrelation trace and optical spectrum of the laser output were measured, as shown Figure 3. Here, the mode-locked laser central wavelength was 1565.3 nm with a FWHM of 2.05 nm. The temporal width of the autocorrelation trace was 2.23 ps corresponding to a pulse width of 1.26 ps, assuming a sech squared pulses, and the time-bandwidth product was 0.318, which is close enough to transform-limited sech squared pulses [14]. Figure 4 shows the measured pulse train of the laser at a repetition rate of 22.7 MHz which corresponds to the laser cavity length about 8.8 m. Finally, a maximum average output power of 4.89 mW was also measured.
4. Conclusion
In summary, we proposed a new technique to fabricate a saturable absorber film using PDMS doped with SWCNTs. Our fabrication method is inexpensive, simple, and highly reproducible. The resulting PDMS/SWCNT thin film can be easily incorporated within an all-fiber laser cavity by simple placing the film between two FC/AFC fiber connectors, which provides a very stable SA device. Self-starting passive mode-locked operation was accomplish by means of this PDMS/SWCNT film and it generated a pulse train at a repetition rate of 23.38 MHz; each one of these pulses has a width of 1.26 ps, and the maximum average optical power was 4.89 mW.

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