

# Passively Mode-Locked Lasers using Saturable Absorber Incorporating Dispersed Single-Wall Carbon Nanotubes

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## Abstract

Passively mode-locked lasers using saturable absorber incorporating dispersed single-wall carbon nanotubes (SWCNTs) is demonstrated. The peak absorption wavelength of saturable absorber can be engineered within the gain bandwidth of erbium-doped fiber (EDF) centered at 1550 nm. The mean diameter of SWCNTs and the linear optical absorption of SWCNTs-polyvinyl alcohol (PVA) film are verified by Raman spectroscopy and UV-Visible-NIR spectrophotometer. By integrating the SWCNTs-PVA film into EDF ring laser (EDFL) centered at 1550 nm, we observed three pulse mode operations, Q-switching, mode-locking, and 5<sup>th</sup>-order harmonic mode-locking. The measured pulsewidths of the mode-locking and 5<sup>th</sup> harmonic mode-locking EDFL are 4.2 ps and 2.7 ps, respectively.

## Introduction

The state of art for the femtosecond laser generation is primarily based on the architecture developed in 1990 [1], employed by the Kerr-lensing modulation scheme for passively mode-locked the Ti:sapphire solid-state laser. The major disadvantage of this laser source is that the mode-locking can not be self-started. In order to have a self-started mode-locking, the passively mode-locker must have an electronic transition involved. Up to now the semiconductor saturable absorption mirrors (SESAM) [2] device is used for self-started mode-locking the laser. However, the SESAM in the passive mode-locking ultrafast laser is fabricated under vacuum environment with MBE and MOCVD processes and further ion implantation to reduce the recovery time.

The SWCNTs [3] have pointed out many interesting physical characteristics due to the quasi one dimension structure. Depending on the chirality of enrolled graphite sheets, the diameter of SWCNT and either semiconducting or metallic tube were determined [4]. Despite the chirality of SWCNT is not easy to control, we still can select the mean diameter and distributed diameter range of SWCNTs having the saturable absorption peak to match the gain window for useful applications channels, such as optical fiber communications, medicine and military. By comparing the difference between SESAM and SWCNTs-based mode-locker in preparing procedures, the SWCNTs-polymer film can be prepared by simple process with low cost.

However the more aggregation of SWCNTs will lead SWCNTs-PVA film the poorer nonlinear optical characteristics in the application, the dispersion of SWCNTs

in the film is necessary. In this study, the optical properties of SWCNTs-PVA film is surveyed in particular for the absorption profile near the EDF lasing wavelength 1550nm. Moreover, the SWCNTs-PVA film is used to be the saturable absorber in the optical fiber ring laser to generate the ultrafast pulse.

## Methods

In this work, the key part of mode-locking generation is the fabrication of saturable absorber incorporating dispersed SWCNTs. To match the EDFL operating at 1550 nm, the choosing of SWCNTs with suitable mean diameter and distributed diameter range is a critical step. In this study, we used two kinds of SWCNTs with different distributed diameter ranges. The distributed diameter range of the first kind of SWCNTs is 1-1.5 nm. The purity is larger than 90 percent. The second kind of SWCNTs is 1.2-1.5 nm. The purity is also larger than 90 percent.

The host material that we used is polyvinyl alcohol (PVA). It is water-soluble synthetic polymer with properties of excellent film forming. However the SWCNTs are very difficult to disperse in the water, we need to disperse the SWCNTs and prevent their reaggregation. Here we used the surfactant, Sodium Dodecylbenzenesulfonate (SDBS), to be the dispersant. It shows the ability of dispersing the SWCNTs and good dispersing stability in the water. [5-7].

The procedures of the saturable absorber fabrication include three major steps. First, we mix the SWCNTs and dispersant in the water to form the hybrid solution. We stirred the hybrid solution by using ultrasonic cleaner about 12hrs to uniformly disperse SWCNTs with suitable ratio of all inclusions. Second, we mixed the PVA with the hybrid solution to form the precursor and stirred it by using ultrasonic cleaner about 6 hours. This step helps us get precursor having enough viscosity and easily being used in forming the SWCNTs-PVA film. Finally, the suitable amounts of precursor are free-standing on the glass substrate, and dry it in the room temperature to form the saturable absorber incorporating dispersed SWCNTs.

In order to check the dispersion degree of the SWCNTs in the hybrid solution, we use the UV-Visible spectrophotometer to check the absorption at 550nm wavelength. Because the individual SWCNTs show the characteristic bands corresponding to additional absorption due to 1D van Hove singularities [8-9]. However, the bundled SWCNTs are hard to attribute in the UV-Visible region [10]. The absorption can

be measured from the ratio of the incident light and the intensity of transmitted light. If we well disperse the SWCNTs in the hybrid solution, more surface areas of the SWCNTs are exposed in the hybrid solution and we can get more chance to absorb and reflect the light of 550nm. Hence, we can get the higher absorbance at 550nm wavelength with better dispersed SWCNTs in the hybrid solution. Besides we also examine the linear optical absorption of the SWCNTs-based saturable absorber by using UV-Visible-NIR spectrophotometer.

For the work of generating mode-locking, we take the saturable absorber incorporating dispersed SWCNTs into the EDFL. The EDFL scheme is shown in Fig.1.

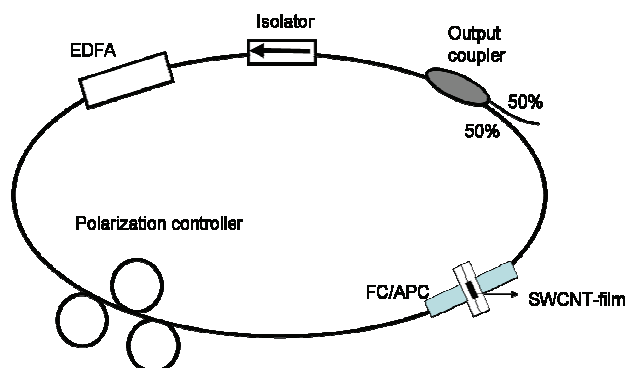


Fig.1 The scheme of EDFL incorporating SWCNT-film

The SWCNTs-based saturable absorber is placed between two FC/PC fiber connectors. The emission light from EDFA passes the saturable absorber and feedbacks into EDFA thorough the output coupler. In the 50% output port of the output coupler, we can get the pulse train and optical spectrum through the oscilloscope and optical spectrum analyzer.

### Measurements and Results

The ratio of SWCNTs and SDBS is a key parameter in order to obtain the high dispersion degree of the SWCNTs in the hybrid solution. We kept the amounts of SWCNTs and changed the amounts of SDBS in the hybrid solution to check the dispersion. The dispersion degrees of the hybrid solution at different ratios of SWCNTs and SDBS were measured by using UV-Visible spectrophotometer. Figure 2 shows the transmission of the hybrid solution with different amounts of SDBS at 550nm wavelength. From fig.2 (a) and (b), we got the lowest transmission when we added 12mg SDBS with both SWCNTs. The lower transmission means that the SWCNTs get better dispersed.

The mean diameter and distributed diameter range of the SWCNTs, important factors in the SWCNT-based saturation absorber, determine the operating wavelength of ML laser based on the corresponding van Hove singularity. Here, Raman spectroscopy is used to check the mean diameter of SWCNTs. Form figure 3, the peak of the breath vibration model is nearby  $156\text{cm}^{-1}$  and about  $1.55\text{nm}$  of the approximate mean diameter is calculated [11]. However, according to the laser pumping at different wavelength, the intensity and peak location will shift, even the level of laser

pumping is very small[12]. Therefore, we can use transmission electron microscope to check the real distributed diameter range of the SWCNTs for minimizing the inaccuracy.

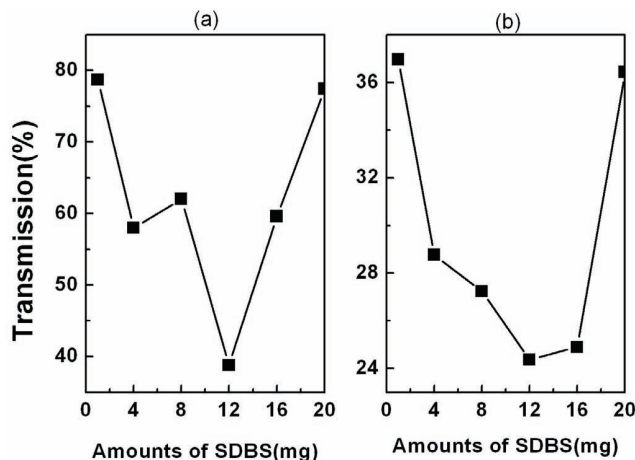


Fig.2 Transmission of hybrid solution at different amounts of SDBS (a) SWCNTs with 1.2-1.5nm (b) SWCNTs with 1-1.5nm

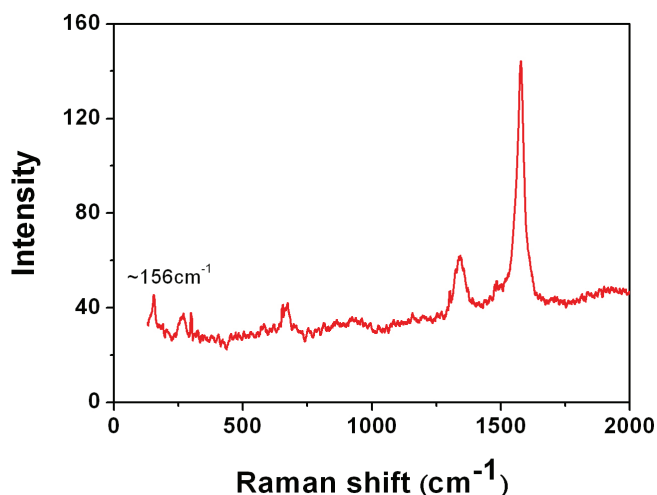


Fig. 3 Raman spectrum of saturable absorber by incorporating SWCNTs with 1.2-1.5nm

The mean diameter and distributed diameter range of SWCNTs determines the operating wavelength of mode locked laser based on the corresponding van Hove singularity. In order to convince the operating wavelength, a UV-Visible-NIR spectrophotometer is taken to measure the linear optical absorption of SWCNTs-PVA film within 400-1800 nm wavelength, as shown in Fig. 4.

From Fig.4, it shows that the peak absorption wavelength of the corresponding 1st van Hove near 1550 nm, locating in the EDF lasing window.

When we used the kind of SWCNTs with 1-1.5nm diameter to make the saturable absorber and incorporated the saturable absorber into EDF ring laser, the pulse trains were caught under 50mW, 70mW, 90mW and 120mW pump powers, as shown in Fig. 5. In low pump power (50mW),

mode-locking operation accompanied with Q-switched operation. As the pump power increased, the Q-switched operation gradually dominated. However, the mode-locking was not observed within the range of pump power that we varied.

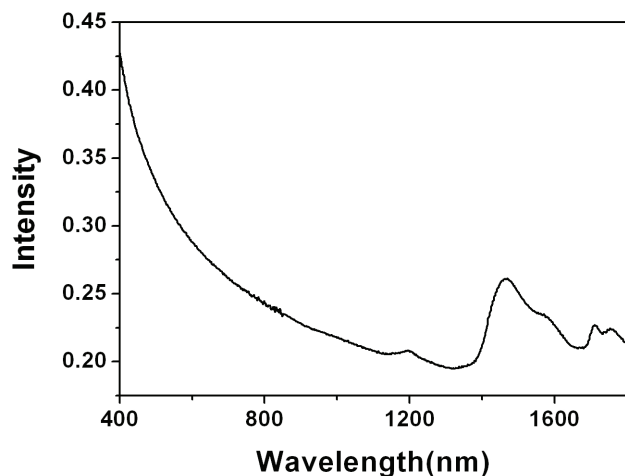


Fig.4 The linear optical absorbance of saturable absorber by incorporating SWCNTs with 1.2-1.5nm

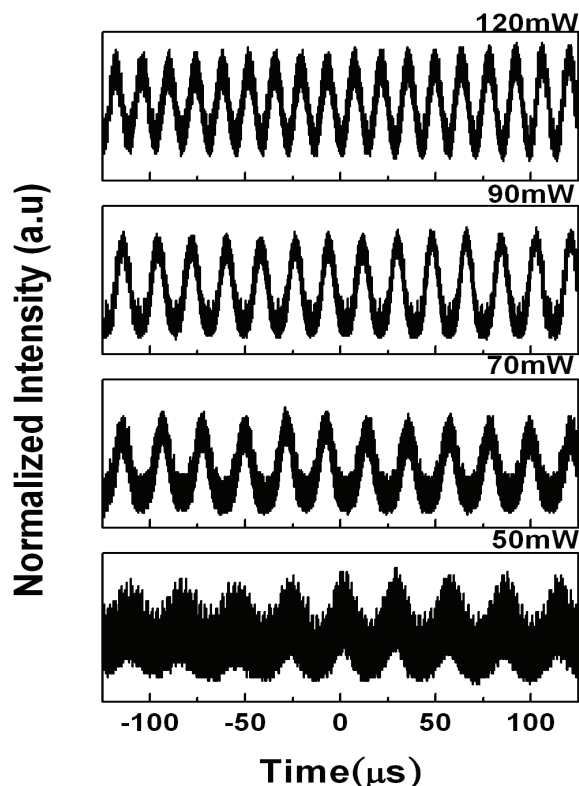


Fig.5 The pulse trains under different pump power.

Fig. 6 shows the pulse trains under different pump level operation when we use the SWCNTs with 1.2-1.5 nm diameter. When the pump power was at 78mW, we observed the mode-locking operation and the repetition rate was about 5 MHz. If we slightly increased the pump power to 81mW, we observed the harmonic mode-locking via a fine adjustment

on the intra-cavity polarization controller. Up to 5<sup>th</sup> harmonic order can be obtained with increasing pumping power and continuously detune the polarization of circulating light inside the cavity. Furthermore, we also observe the pulse-amplitude inequivalent situation when switching the mode-locking into harmonic mode-locking condition. Although we can obtain higher repetition rate, the pulse energy is not stable. When the pump power reached 144 mW, the Q-switched operation happens.

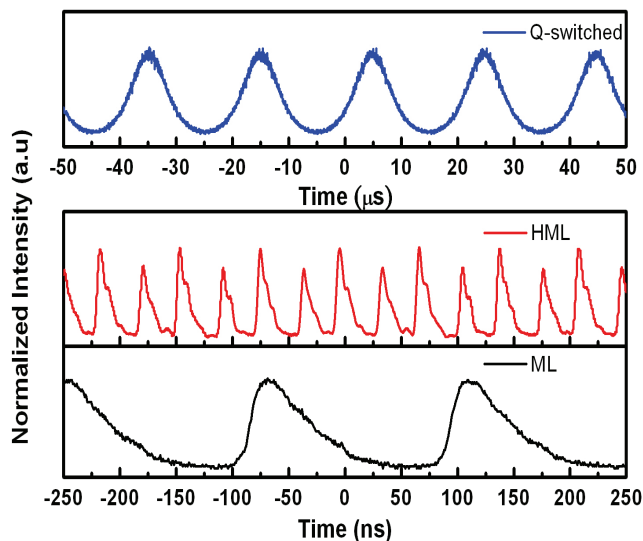


Fig.6 The pulse trains under different operation modes

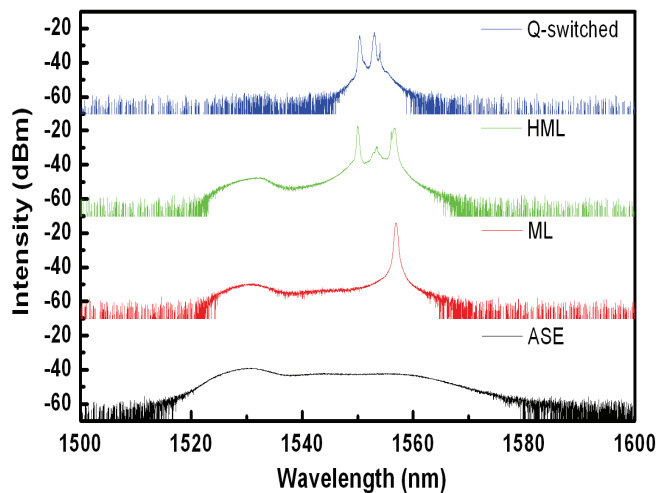


Fig.7 The optical spectrum under different operation modes

Figure 7 shows the optical spectrum of the output. From the optical spectrum of the mode-locking, we noted that the spectrum was centered at about 1550 nm. The spectra were taken right after the output of the EDFL. Except the Q-switching operation of the EDFL which exhausts all of the EDF gain, the mode-locking and harmonic mode-locking modes fails to employ the whole EDF gain during operation and leaves the residual gain for the amplified spontaneous emission. Consequently, the mode-locking and harmonic

mode-locking output pulses are relatively small as compared to the Q-switched one. Nonetheless, we have observed that the harmonic could exhibit a relatively broadened spectrum as compared to the mode-locked one, indicating that the harmonic mode-locking pulse could benefit from shorter pulsewidth.

The auto-correlator traces of the mode-locking and harmonic mode-locking EDFL with the SWCNT-based saturable absorber were shown in Fig. 8. For mode-locking case, the full-width half-maximum (FWHM) of mode-locking EDFL pulse width measured by the auto-correlator is about 6 ps before de-convolution. In comparison, the 5<sup>th</sup> harmonic mode-locking pulse is slightly shorter with an auto-correlated pulse width of 3.8 ps. After de-convolution, the corresponding pulse width for mode-locking and harmonic mode-locking 4.2 ps and 2.7 ps, respectively. It is easily found that these pulses has yet not entered transform limited regime as their related time-bandwidth products are still far away the transform-limit condition. Further intra-cavity dispersion compensation has to be considered, however, such configuration will be more complicated due to the mismatching mode-field between the dispersion compensating segment and the original single-mode fiber ring.

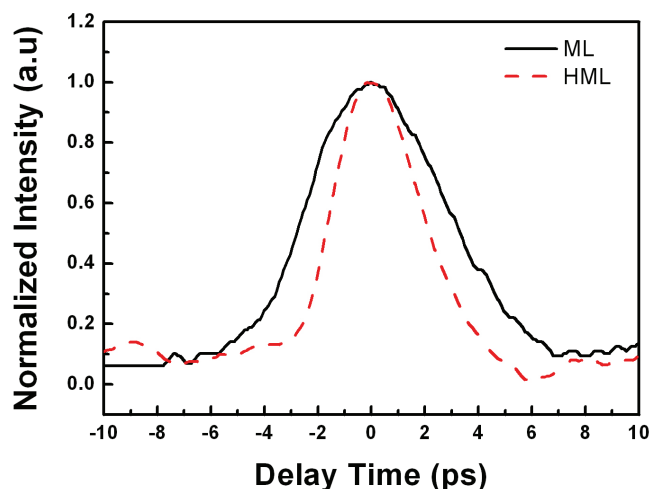


Fig.8 The auto-correlator trace under mode-locking and harmonic mode-locking

Therefore, by integrating the SWCNTs-PVA film into EDFL centered at 1550 nm and by adding intra-cavity polarization controller, we observed three different pulsation operation modes, including the Q-switching, mode-locking, and harmonic mode-locking. The measured pulse widths of the mode-locking and 5<sup>th</sup> harmonic mode-locking are 4.2 ps and 2.7 ps, both of them fail to compete with the amplified spontaneous emission for the EDF gain. This phenomenon also interprets that the pumping power requested for the mode-locking threshold could be lower than estimated. During the experiments, the output instability problem frequently happened to interrupt the mode-locking or harmonic mode-locking mechanism. Further investigations at lower pumping power (but beyond the mode-locking

threshold) are necessary for the EDFL to obtain better mode-locking power performance with higher stability.

## Conclusions

Passively mode-locked lasers using saturable absorber incorporating dispersed SWCNTs was demonstrated. The distributed diameter range of SWCNTs is a critical parameter to generate mode-locking operation. Thorough integrating the well-dispersed SWCNTs-based saturable absorber into EDFL for axial modes-locking, we were able to generate the Q-switched, harmonic mode-locking and mode locking operation on different pump power. The measured pulsewidths of the mode-locking and 5<sup>th</sup> harmonic mode-locking EDFL are 4.2 ps and 2.7 ps, respectively.

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