# Characterization of Dynamic Nonlinear Absorption of Carbon Nanotube Saturable Absorber

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**Abstract**: Dynamic nonlinear absorption of composite-type single-wall carbon nanotube saturable absorbers is characterized using both femtosecond and picosecond pump pulses. Results are compared with numerical simulations based on two commonly used saturable absorber models.



**OCIS codes:** (160.4330) Nonlinear optical materials; (230.4320) Nonlinear optical devices.

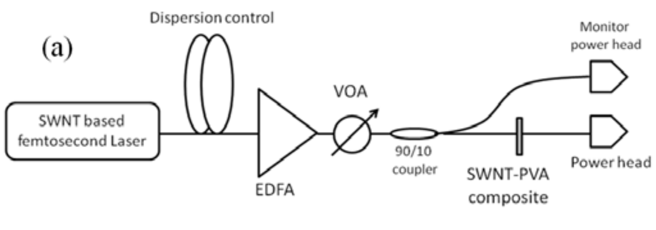
## 1. Introduction

Recently, Single-Wall Carbon Nanotubes (SWNTs) are rapidly emerging as a new type of saturable absorbers for ultrafast mode-locked fiber lasers [1-6]. Compared with conventional technologies, such as SESAMs (Semiconductor Saturable Absorber Mirrors), SWNTs based saturable absorbers possess key advantages such as wide operating bandwidth, ultrafast (<1ps) recovery time and wide spectral coverage [1-6]. Despite the growing number of papers on SWNT mode-locked fiber lasers, no study on the dynamic nonlinear absorption of SWNTs saturable absorbers have been reported. Therefore, it is still unknown whether existing saturable absorber models would be sufficient to depict their intracavity operation dynamics. Investigation into this area may also lead to development of saturable absorber models for these new materials and facilitates their applications in customized mode-locked laser design.

In this paper, we study the dynamic nonlinear absorption of a SWNT-Polymer composite type saturable absorber by using a SWNT mode-locked ultrafast fiber laser. The output pulse durations from the laser can be tuned from ~200fs to 10ps, a change of ~50 fold, by external dispersion control. The experimental results are subsequently compared with numerical simulations of the dynamic nonlinear absorption measurements based on two well known saturable absorber models and we find that at relatively longer pump pulse durations, an ideally fast saturable absorber model can better account for SWNT absorber's dynamic absorption. However, neither model can account for the behaviour of the SWNTs absorber observed at a regime where pump duration is pronouncedly shorter than the recovery time of the absorber i.e. pump duration ~ 230 fs.

## 2. Experimental Setup and Results

The experimental setup for the dynamic nonlinear absorption measurement is illustrated in Fig.1a. The pump pulses are from a femtosecond fibre laser operating at a center wavelength of 1561nm and a repetition rate of 20.3MHz. The output pulse from the femtosecond fiber laser is amplified by a commercial Erbium-doped Fiber Amplifier (EDFA). By varying the length of the SMF-28 fibre between the initial femtosecond source and the input to the EDFA, it is possible to adjust the pump duration from 230fs to 13ps. A computer controlled variable optical attenuator (VOA) is inserted after the EDFA to change the input power to the saturable absorber device in steps of ~ 0.3dB and a fibre coupler is used to monitor the duration as well as average power of incident pump pulses. The autocorrelation traces of the pump pulses are shown in Fig. 1b. After amplification, no pulse shape distortion is observed, keeping pulse duration adjustable from 230 fs to 13ps.



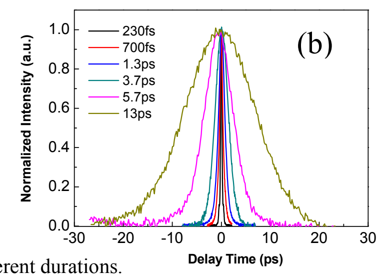




Fig.1 (a) Experimental setup (b) Pump pulses with different durations.

For the dynamic nonlinear absorption measurement, the saturable absorber film used is a 50 μm thick, SWNT-PVA (Polyvinyl alcohol) composite film. It is coupled between two FC/PC fibre ferrules using optical index matching gel [1]. Fig.2(a) illustrates the composite device's absorption as a function of pump average power, with the pump duration as a variable parameter. It can be seen that shorter pump durations correspond to deeper modulation depth, which is normally expected for a fast saturable absorbers. Fig. 2(b) shows the same data in saturable absorption vs.

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peak power. Note that the data is normalized to the saturable part (10%) of the device's absorption to better illustrate the trends. Clearly, at relatively long pump durations, the absorption curves show trends to converge while at relatively short pump duration i.e. ~ 230 fs, appreciable deviation from the other absorption curve is present.

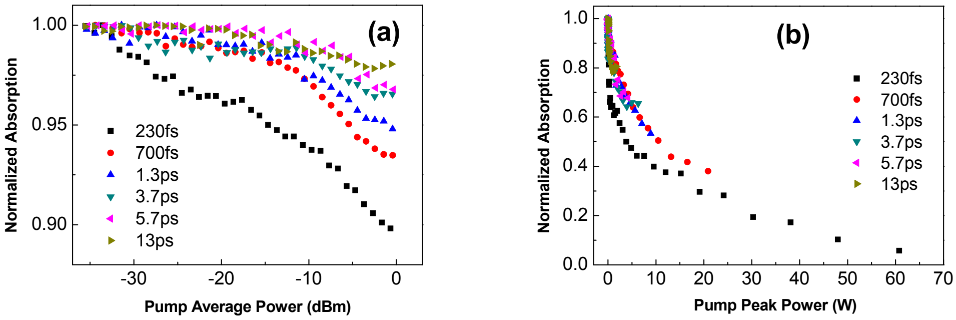


Fig.2 Nonlinear absorption as a functions of pump average power (a) and pump peak power(b).

To provide a reference for the experimental observation in Fig.2(b), numerical simulations based on two commonly used saturable absorber models, namely a finite recovery time saturable absorber and an ideally fast saturable absorber model, are carried out [7]. The corresponding model equations are shown in the figure 3 (a) and (b), where $q_0$, $\tau_{sa}$, and $I_{sat}$ denote saturable absorption, absorber recovery time and saturation power respectively. As the main objective is to resolve the dependence of dynamic absorption on pump durations, we normalize the pump peak power to that of the saturable absorber's saturation power. The $q_0$ is set to 0.1 and the recovery time for the finite recovery time absorber $\tau_{sa}$ is set to 1.0 ps. A number of incident pump durations (assuming a *Sech*$^2$-shaped pump intensity profile) are used to simulate the dynamic nonlinear absorption experiment. The results are shown in Fig.3 (a) and Fig.3(b). Changes to the value of $q_0$ and $\tau_{sa}$ are found to exhibit no effect on the trends of the dynamic absorption curves shown in Fig.3.

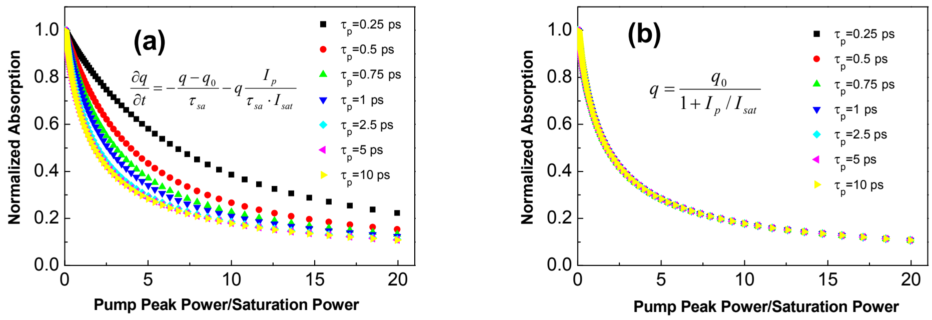


Fig.3 Dynamic nonlinear absorption curves for (a) a finite recovery time absorber model (b) an ideally fast absorber model.

Comparing Fig.2(b) with Fig.3, it is clear that for relatively long pump duration range ($\tau_p$>0.75$\tau_{sa}$), the ideally fast saturable absorber model can reasonably well simulate the experimental results. However, at shorter pump durations, SWNT composites absorber exhibit appreciable deviation from theoretical curves of both models, especially the finite recovery time model. This may come from the fact that SWNTs demonstrate relatively large nonsaturable loss and thickness so a thin-absorber assumption for the finite absorber model is not valid [7]. For ideally fast saturable absorber, the slight discrepancy with experimentally observed curve at shorter pump duration ~ 230 fs is probably due to fact that pump duration of 230 fs is shorter than the typical recovery time of SWNTs [8]. Thus the model condition of ideally fast absorber is not met.

In summary, we have for the first time investigated the dynamic nonlinear absorption of composite-type SWNT saturable absorbers depending on pump pulse duration. This provides important information about their dynamic intracavity performance in the context of laser mode-locking, especially to understand the intracavity pulse shaping mechanism. Further investigation in this direction may lead to full development of models for ultrafast pulse generation using such SWNTs based saturable absorbers.

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