



## Wall paper single-walled carbon nanotubes absorber for passively mode-locked Nd: GdVO<sub>4</sub> laser

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### ABSTRACT

A novel and low-cost wall paper single-walled carbon nanotubes (SWCNTs) absorber was fabricated by high viscosity of polyvinyl alcohol (PVA) aqueous solution and vertical evaporation technique. Sandwich structure wall paper SWCNT (SSWA-SWCNT) absorber was constructed by a piece of wall paper SWCNT absorber, a piece of round quartz and an output coupler mirror. We exploited it to realize mode locking operation in a diode-pumped Nd: GdVO<sub>4</sub> laser. A pulse duration of 9.6 ps was produced with an average power of 870 mW. The stable mode locking operation was obtained when the average power is less than 300 mW.

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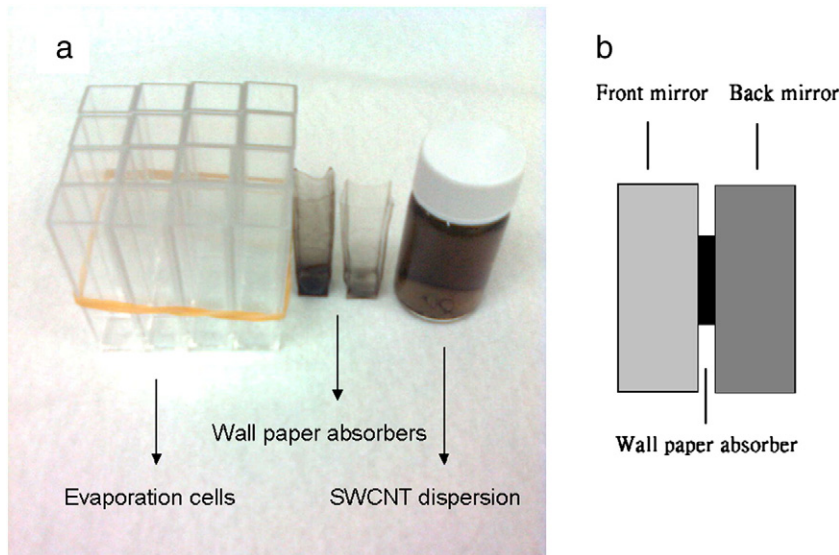
Currently, passively mode locked pulse lasers are obtained mostly from the mode-locked lasers by semiconductor saturable absorber mirrors (SESAMs) [1]. But the fabrication of SESAM requires very complex and costly epitaxial grow processes. Furthermore, the wavelength of the operation range for SESAMs is limited by the materials. Hence, a new material with stronger optical nonlinearity, a broader operation range and simple procedures of fabrication are demanded. Carbon nanotubes have been investigated since they were discovered due to their unique electric and optical properties [2]. Because of the fast recovery time, which covers a broad spectral range in the near infrared, and excellent chemical stability, semiconducting SWCNT is a promising material for saturable absorbers in laser mode locking [3–10]. However, there are two problems to be resolved for practical mode locking application. One problem is that the output laser power with SWCNT absorber is not as large as that with SESAMs. Most of the reported mode-locked lasers with SWCNTs are single mode fiber lasers and they provide only several mW of laser output, which is insufficient for many applications. In order to get higher output power, mode locked solid-state lasers with SWCNTs are required [11–15]. By far most of the SWCNT absorbers in solid-state lasers are fabricated by spin coating technique, and thus SWCNT/Polymer composite has to be used, which limits the output power below 1 W because high power laser will result in deformation in polymer. To obtain high power ultrafast lasers, polymer-free SWCNT absorber and growth method for orderly SWCNTs distribution film was used [16–20]. The other problem for mode-locked lasers with SWCNT is pulse instability in high power

mode locking operation. Singlet oxygen molecules can be generated and damage SWCNT when common oxygen molecules at atmosphere are photo-excited by high power laser, which will lead to mode-locked lasers unstable at high power (above 100 mW). Generally, stable operation of high power mode locking can keep only several minutes or 10 min or so at atmosphere. Coating dielectric film can efficiently lengthen the duration of stable operation but significantly increase the cost and counteract the advantage of low cost for SWCNT absorber. In this letter, we demonstrated wall paper absorber and sandwich structure wall paper SWCNT (SSWP-SWCNT or composite) absorber. By using SSWP-SWCNT absorber, as high as 300 mW output power was obtained from mode-locked laser in stable operation.

The SWCNTs used in this experiment were grown by electric arc discharge technique. The mean diameter of the SWCNTs is about 1.5 nm. First, several milligrams of SWCNT powder were poured into 10 ml 0.1% SDS (sodium dodecyl sulfate) aqueous solution. Here SDS was used as a surfactant. In order to obtain SWCNT aqueous dispersion with high absorption, SWCNT aqueous solution was ultrasonically agitated for 10 h. After the ultrasonic process, the dispersed solution of SWCNT was centrifuged to induce sedimentation of large SWCNT bundles. After decanting the upper portion of the centrifuged solution, some PVA powder was poured into the solution and dissolved at 90 °C with ultrasonic agitation for 6 h. Then, the SWCNT/PVA dispersion was diluted and poured into a polystyrene cell as shown in Fig. 1(a). Finally we put these cells in an oven for evaporation. The temperature of the oven was kept at 40 or 45 °C. It took about one or two days for complete evaporation. When the evaporation was finished, the wall and the bottom of the cell were coated with a thin plastic film. The PVA aqueous solution has strong viscosity to the polystyrene cell so that it adheres to the wall of the cell. When the cell was dry, the PVA

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**Fig. 1.** (a) The left is the polystyrene cell for the growth of absorber. The right is the SWCNT/PVA dispersion. The wall paper absorber with different density of SWCNT is in the middle. (b) Sandwich structure wall paper SWCNT absorber. The front mirror is a round quartz. The back mirror is a round quartz, an output coupler or a high reflectivity mirror.

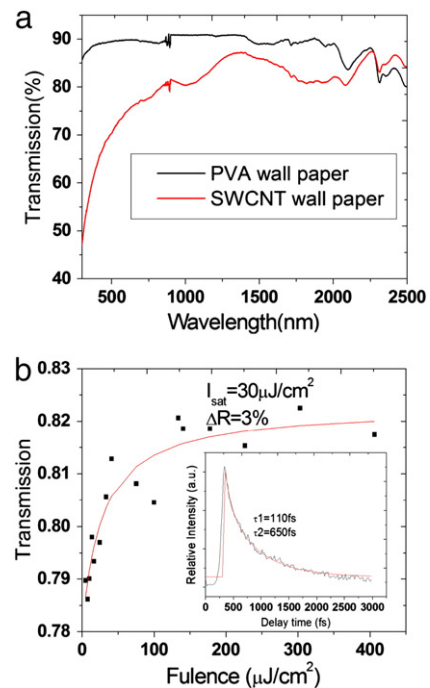
film lost the viscosity to the cell, so we can strip the PVA film cell off the polystyrene cell by a tweezers easily. The SWCNTs were carried by PVA to the surface of the wall and the bottom of the polystyrene cell during the evaporation process. The SWCNT/PVA film on the wall of the cell had higher quality than that on the bottom so that we can use the former as absorber for mode locking and hereafter we call it as “wall paper SWCNT absorber”. The procedure to fabricate wall paper absorber is very simple. The wall paper absorber cell was very cheap. We choose middle part of the wall paper absorber for mode locking because the middle part of the wall paper is more uniform. In practice, we cut off the wall paper absorber cell into many pieces for use in mode locking. By this way, the cost of the absorber is further reduced.

The wall paper absorber can be directly used for mode locked fiber laser. However, the absorber cannot be directly used for solid state laser mode locking because it is not freestanding. To use in the solid-state lasers, we design a sandwich structure as Fig. 1(b). We can adjust the transmission of the back mirror so that the combined absorber has flexible method in the cavity. In this investigation, we adopt output coupler as the back mirror. An UV–Visible–NIR spectrophotometer was employed to measure the linear optical transmission of the PVA wall paper and SWCNT/PVA wall paper absorber, as shown in Fig. 2(a). (The PVA wall paper is fabricated by PVA solution, not the SWCNT/PVA composite dispersion.)

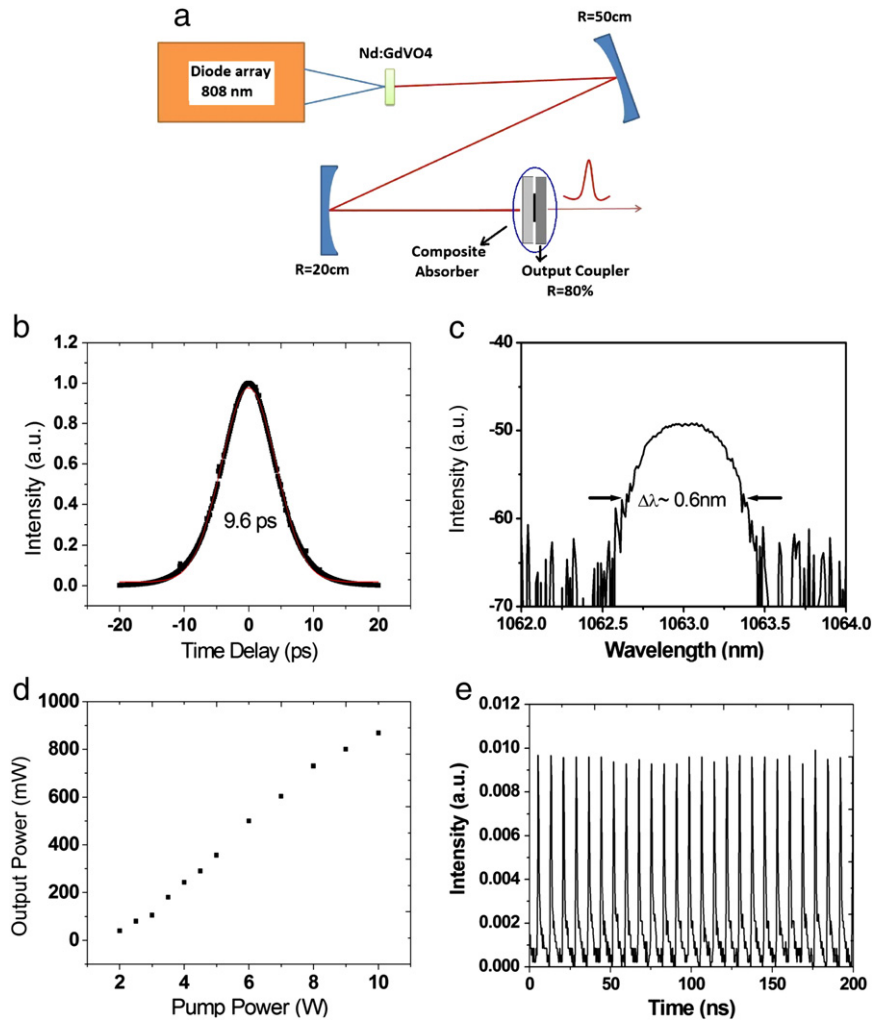
Fig. 2(b) shows the transmission of the wall paper absorber with increasing pump fluence measured in a Spectra-Physics ultrafast laser system. We measured the modulation depth of the SWCNT absorber at 1060 nm. The modulation depth of the absorber is about 3% and the saturable pump fluence is about  $30 \mu\text{J}/\text{cm}^2$ . The reflection loss of both side of the pure quartz is about 8%. So we can estimate that non-saturable loss of the SWCNT absorber is about 9%. The inset in Fig. 2(b) shows the ultrafast transient absorption trace. It reveals an instantaneous rise followed by two exponential decays with time constants of 110 fs and 650 fs, respectively. The result shows that as fabricated SWCNT absorber has a very short recovery time which is sufficiently for the ultrafast laser.

The schematic setup of our laser with folded z-configuration is shown in Fig. 3(a). A fiber-coupled diode-array laser with center wavelength of 809 nm was used as the pump source. The laser crystal is a  $3 \times 3 \times 8 \text{ mm}^3$  a-cut Nd:GdVO<sub>4</sub> crystal (with 0.5-at.% Nd<sup>3+</sup> concentration). One side of laser crystal is high reflection (HR) coated at 1064 nm and anti-reflection (AR) coated at 808 nm as an end

mirror of the resonator; while the other side with 2° wedge is AR coated at 1064 nm. Two curved mirrors with radii of curvatures of 500 and 200 mm, were used as folding mirrors to conduct cavity beam through composite (SSWP-SWCNT) absorber as well as an output coupler. We can estimate the beam diameter at the absorber to be about  $72 \mu\text{m}$ . We chose output coupler mirror with reflectivity of 80% at 1064 nm to generate mode locked laser. It should be noted that the wall paper absorber should be pressed tightly by the output coupler mirror and round quartz to isolate the wall paper from the air. Otherwise, the mode locking could be unstable. The black squares in Fig. 3(b) show the measured profile of autocorrelation signal with the width (FWHM) of 9.6 ps. The line is the Gaussian fitting line.



**Fig. 2.** (a) Linear transmission curves of PVA wall paper and SWCNT/PVA wall paper absorber (SWCNT/PVA was briefly marked as SWCNT in the diagram). (b) Transmission of wall paper absorber with increasing pump fluence. Inset is the recovery time of the absorber.



**Fig. 3.** (a) Experimental setup of the mode locked laser. Composite absorber was the absorber as well as the output coupler. (b) Autocorrelation trace of the 9.6 ps pulse. (c) Optical spectrum of mode locked laser. (d) Average output power versus pump power. (e) Mode-locked pulse train.

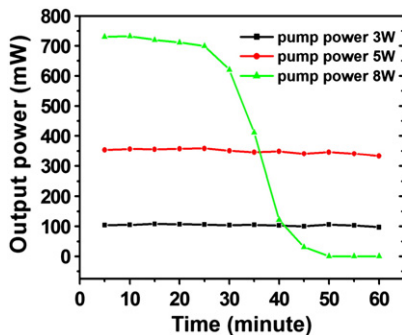
Fig. 3(c) shows the corresponding optical spectrum. The spectral FWHM of the mode locked laser is about 0.6 nm. The time bandwidth product is 1.5, which is larger than the transform-limited value of 0.44 for Gaussian pulses, indicating that the mode-locked pulses are frequency chirped and their duration of the pulses could be further compressed. The average output power as a function of the pump power is shown in Fig. 3(d). The laser threshold, maximum output power and slope efficiency are 2 W, 870 mW and 10%, respectively. Fig. 3(e) shows the pulse train at the CW mode locking operation with repetition of 125 MHz. Fig. 4 shows the long-term operation

of mode locked Nd:GdVO<sub>4</sub> laser with SSWP-SWCNT absorber at different pump power. It is clearly indicated that the fluctuation of output power is very small when the pump power is below 5 W. However, when the pump power is higher than 8 W, the output power start to decrease after 25 min and get to zero after 50 min, which indicates that the PVA was destroyed. By the steady state test, we found that the SWCNT/PVA can work well below 300 mW. Such an ultrafast laser can be used for seed laser source for amplifying system. Further optimization is required in the laser cavity and fabrication of the SWCNT wall paper absorber for higher output power in stable operation.

In conclusion, we have demonstrated a novel sandwich structure wall paper SWCNT absorber. The fabrication procedure and optical characteristics were described. Stable operation of mode locked laser has obtained when the average output power is less than 300 mW. The core of the absorber is wall paper SWCNT absorber, which is simple fabrication and very low cost. Such a SWCNT absorber has potential to be applied to industry for sub-Watt ultrafast lasers in the future.

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**Fig. 4.** The long term stable operation of mode locking at different pump power.

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