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Watt-level high power passively mode-locked Nd:LuVO$_4$ laser with carbon nanotube saturable absorber at 1.34 μm

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ABSTRACT

The first Nd:LuVO$_4$ ultrafast mode locking laser operating at 1.34 μm is demonstrated by utilizing a polymer free single-walled carbon nanotube (SWCNT) absorber fabricated by the vertical evaporation technique. The fast recovery times of the absorber were measured to be 40 fs and 820 fs. The modulation depth of the absorber was about 2%. Passively mode-locked Nd:LuVO$_4$ laser using this absorber was demonstrated. As high as 1.74 W continuous wave mode-locked pulses have been achieved with the pulse duration of 18 ps and the repetition of 125 MHz. Such kind of absorbers have great potential to be put into practical use because of their merit of high damage threshold, broad operational wavelength range and low cost of fabrication.

1. Introduction

Near 1.3 μm mode locked solid state laser source is a particularly attractive option for the high-speed optical communication system [1]. High peak power 1342 nm lasers can be frequency converted into the 671 nm by second harmonic generation or into the 447 nm by third harmonic generation. Laser source operating at 1.3 μm can also serve as a pump source for generating mid-infrared laser near 3 μm [2]. Nd:LuVO$_4$ is well known for its large absorption and stimulated emission cross sections [3]. Broad fluorescence gain bandwidth and higher damage threshold are favorable for generating high average power ultra-short pulses via mode locking operation [4]. Traditionally, InGaAs [5], GaInNAs [6] AlGaInAs [7] based semiconductor saturable absorption mirrors (SESAMs) PPMgSLT [8], PPLN [9] and V:YAG [1,10] at the wavelength of 1.3 μm have been used for passively mode locking applications. However, most of V:YAG mode locked lasers are Q-switched and mode-locking operation and continuous mode locking operation are difficult to be obtained. The temperature of PPLN should be raised to over 200 °C to meet the phase-matching point in mode locking operation [9], which make the laser system very complicated. SESAMs have the short-comings such as long lifetime, complicated fabrication procedure, high cost, narrow operation wavelength band [11–14]. Therefore new materials with broader operational wavelength range, low cost, short recovery time are demanded. SWCNT is a promising material for saturable absorbers in laser mode locking [15]. In order to get higher output power, mode locked solid-state lasers are needed. Q-switched mode locking Nd:GdVO$_4$ laser at 1340 nm was realized by using SWCNT absorber [16], most of which have been used in mode locking lasers are Polymer composite base so that their average output power is limited. In 2012, SWCNT-PMMA composite absorber was used to mode locked Nd:YVO$_4$ laser at 1342 nm, continuous wave mode locking was obtained with as high as 0.8 W average output power [17]. However, polymer material tend to be softened or burned upon high power laser [18,19]. In this letter, the vertical evaporation method [20] has been adopted to fabricate a polymer-free SWCNT absorber used in the high average output power Nd:LuVO$_4$ mode locked laser operating at 1.34 μm and hence can generate mode-locked pulses with a repetition rate of 125 MHz and pulse duration of 18 ps in the Nd:LuVO$_4$ laser. The output power of mode locking laser is 1.74 W. To the best of our knowledge, it is the first demonstration of the 1.34 μm mode locked laser by using polymer free SWCNT absorber, which shows the possibility for high power mode locking applications as the maximum output power is above 1 W.

2. Fabrication and characterization of the SWCNTs absorber

The fabrication procedure of SWCNT absorber is similar to that in Ref. [18]. The difference is a 100 nm thick dielectric protective film was coated on both sides of the absorber used for this experiment in order to isolate the SWCNT from the air to increase the optical damage threshold.

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An UV–Visible-NIR spectrophotometer was employed to measure the linear optical transmission of the SWCNT absorbers, as shown in Fig. 1. Generally a low initial transmission of the absorber is not preferable in the low gain solid-state laser cavity. Therefore, among the three samples, it is predicted the sample “SWCNT 0.15 mg” will give better performance and thus it was chosen for the laser experiment as long as it provide enough nonlinear absorption. Fig.2 shows the Raman spectrum from the SWCNT [21] absorber (before dielectric film coating), which was excited by a 488 nm Ar ion laser to produces Raman spectrum as shown in Fig.2, which reveals the three characteristic peak RBM (radial breathing mode), 1D band (the disorder-induced D-band) and 1G band (tangential G band derived from the graphite-like in-plane mode) of SWCNT (RBM peak at 160 cm^{-1}, 1D peak at 1346 cm^{-1}, 1G peak at 1588 cm^{-1}). RBM peak near 150 cm^{-1} is the characteristic peak of SWCNT. 1D peak is from the structural imperfections of the SWCNT. 1G is the graphite peak. The high 1G/1D ratio implies the good quality of SWCNT.

The nonlinear parameters of the SWCNT absorber were measured through an OPO femtosecond laser pump probe system at 1340 nm. The ultrafast laser source is a Spectra-Physics ultrafast laser system including a Tsunami femtosecond oscillator, Spitfire Pro regenerative amplifier and TOPAS-C optical parametric amplifier, which provides 100 fs laser pulses with tunable wavelength from 300 nm to 2000 nm at a 1 kHz repetition rate.

Fig. 3(a) shows the transient absorption trace which reveals a nearly instantaneous rise followed by two exponential decay time constants of 40 fs and 820 fs respectively. The faster component (40 fs) is attributed to the fast carrier being cooled by phonon scattering and the slower one (820 fs) is attributed to the absorption recovery time. The result shows the SWCNT absorber has sufficiently short recovery time for the generation of ultrafast pulse width down to fs level. Fig. 3(b) shows the transmission rate of SWCNT absorber (SWCNT 0.15 mg) with increasing pump fluence measured by the ultrafast laser system at 1340 nm. The modulation depth of the SWCNT absorber was about 2% and the saturable pump fluence is about 30 μJ/cm^2. From Fig. 3(b), the reflectivity of each surface of pure quartz is ~4%, so it is estimated that the non-saturable losses of the SWCNT absorber is less than 2%.

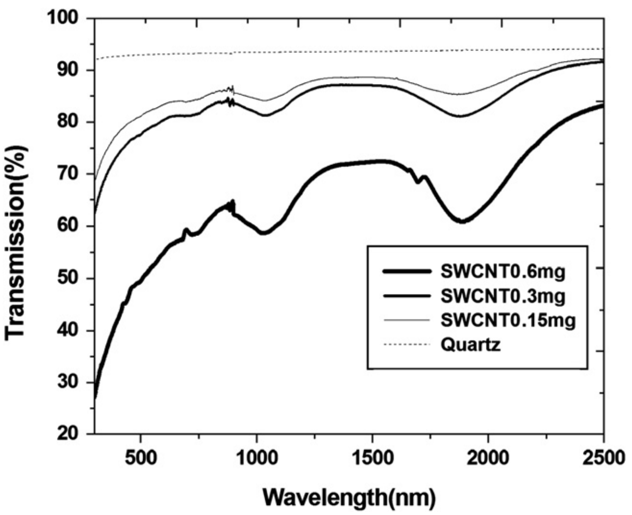

Fig. 1. Linear transmission curves of quartz and SWCNT absorbers fabricated by SWCNT aqueous dispersion at different concentrations.

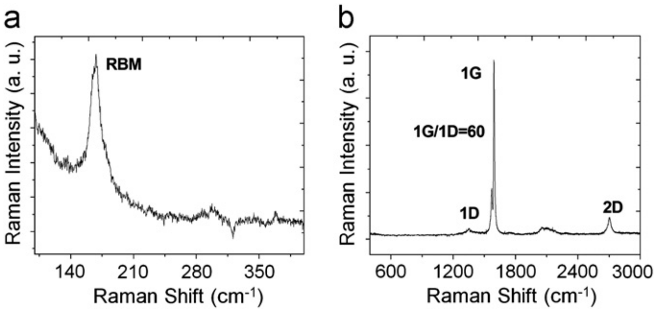

Fig. 2. Raman spectrum of the SWCNT absorber.

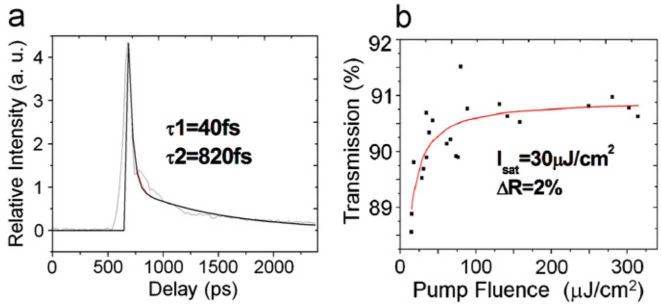

Fig. 3. Nonlinear parameters of the SWCNT absorber. (a) Recovery time. (b) Nonlinear transmission rate.

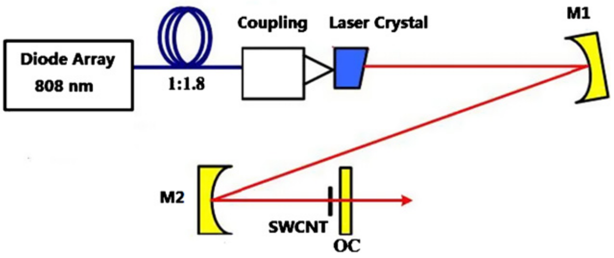

Fig. 4. Experimental set-up of the mode-locked laser.

3. Mode-locking operation

The *z*-type experiment set-up is shown in Fig. 4. The spot size radius of the pump beam in the gain medium is about 225 μm. The α cut Nd:LuVO$_4$ crystal used in the experiments has the dimension of $4\times4\times8$ mm^3 and the Nd^{3+} ions doping concentration is 0.5%. The pump end surface of the Nd:LuVO$_4$ crystal is high-reflection coated at 1340 nm and anti-reflection coated at 808 nm pumping wavelength. The other side of the crystal with 2° wedge is AR coated at 1340 nm and 808 nm. The laser cavity consists of two concave mirrors M$_1$ (the radius of curvature, $R=500$ mm) and M$_2$ ($R=200$ mm), and output coupler with reflectivity of 90% at 1340 nm. The SWCNT was set at 3–5° deviating from the normal incidence.

The black squares in Fig. 5(a) are the measured profile of autocorrelation signal with the width (FWHM) of 18 ps and the line is the Gaussian fitting of the black squares. Fig. 5(b) shows the corresponding optical spectrum. The spectral FWHM of the mode locking laser is about 0.6 nm. The time bandwidth product is 1.8, which is larger than the transform-limited value of 0.44 for Gaussian pulse, indicating that the mode-locked pulses are frequency chirped and their duration could be further narrowed. The measured average output power as a function of the pump power is shown in Fig. 5(c). The CW mode locking is self-starting

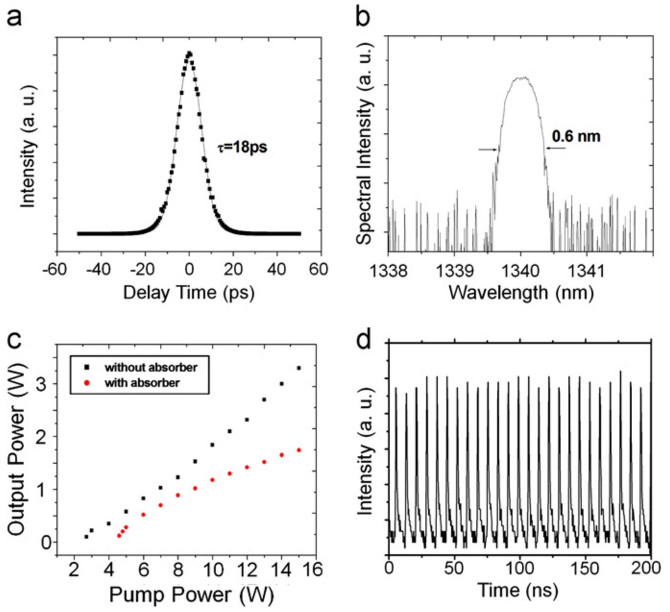

Fig. 5. (a) Autocorrelation trace of the 18 ps pulse. (b) Optical spectrum of mode locked laser. (c) Average output power versus pump power. (d) Mode-locked pulse train.

and is observed when the pump power is above 9 W. The Q-switched mode locking is obtained when the pump power is less than 9 W. For CW operation without the intra-cavity absorber inserted, the laser threshold, maximum output power and slope efficiency are 2.6 W, 3.3 W and 26.8% respectively. For CW mode locking operation with the intra-cavity absorber inserted, the laser threshold, maximum output power and slope efficiency are 4.5 W, 1.74 W and 16.6% respectively. The output power cannot be further scaled up due to the limited pump power available. As shown in Fig. 5(d), the repetition rate of the CW mode locking pulses train is measured to be 125 MHz. Its long term pulse fluctuation is about 5%.

Carbon based absorbers such as carbon nanotubes and graphene have attracted much attention in recent years. However, so far no high power carbon nanotubes based or graphene based absorbers mode-locked lasers operating at near 1.3 μm have been reported. The CNT absorber fabricated by vertical evaporation method has less impurity and thus reducing scattering losses because the CNTs are more orderly arranged on the substrate. The absorption spectrum shown in Fig. 1 indicates the absorber has broad operational wavelength range (from visible to mid-infrared). In fact, the recent passive Q-switched and mode-locked Tm^{3+}:YAP laser operating at 2011 nm confirms that such absorber can be used up to the mid-infrared region [22]. Therefore, it is expected that this SWCNT absorber can be used at a broad operational wavelength range.

4. Conclusions

We have fabricated single-walled carbon nanotubes absorber by vertical evaporation method. With this absorber, high power ~1.74 W stable continuous wave mode locked $Nd:LuVO_4$ laser was operated at 1340 nm with pulse duration of 18 ps and repetition rate of 125 MHz. The experimental results indicate that the fabricated saturable absorber could be practically used to generate high power mode locked laser and can potentially be used over a broad wavelength range up to mid-infrared region.

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