Multi-walled carbon nanotube as a saturable absorber for a passively mode-locked Nd:YVO_4 laser

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Abstract
Within the family of carbon nanotubes, multi-walled carbon nanotube material has the advantages of low-cost and high laser damage threshold. Therefore, in principle, it is more suitable for high power laser applications. In this letter, a high power continuous wave mode-locking Nd:YVO_4 laser using a multi-walled carbon nanotube absorber has been successfully demonstrated. An average output power as high as 1.4 W has been achieved with a slope efficiency of 24%. The repetition rate and pulse width of the mode-locked laser were 68 MHz and 15.5 ps, respectively. The calculated pulse energy and peak power were 20.6 nJ and 1.33 kW, respectively.

(Some figures may appear in colour only in the online journal)

1. Introduction

Ultrafast laser pulses with high repetition rate and pulse energy are mostly obtained from passively mode-locked lasers with semiconductor saturable absorption mirrors [1–4]. Over the last decade, single-walled carbon nanotube (SWCNT) material used as a saturable absorber has been widely investigated in fiber lasers because of its fast recovery time and broad spectral range in the near infrared [5–7]. In addition, passively mode-locked solid-state lasers using a SWCNT absorber have also been developed in order to further scale up the average output power [8–12]. Recently, graphene [13–17], graphene oxide [18], and double-walled carbon nanotube (DWCNT) [19] material have been used as absorbers in succession to mode-locked solid-state lasers.

In this letter, a novel carbon-based multi-walled carbon nanotube (MWCNT) absorber has been used for mode locking of a solid-state laser. MWCNT is the first type of carbon nanotube discovered among the family of carbon nanotube material [20]. The early stages of mass production of MWCNT material have been achieved. The growth of MWCNT material does not need complicated techniques or special growing conditions so that its production yield is high for each growth. Therefore the production cost of MWCNT material is about 1/2–1/5 of that of SWCNT material [21]. Additionally, MWCNT material has good thermal characteristics, which is of great importance for

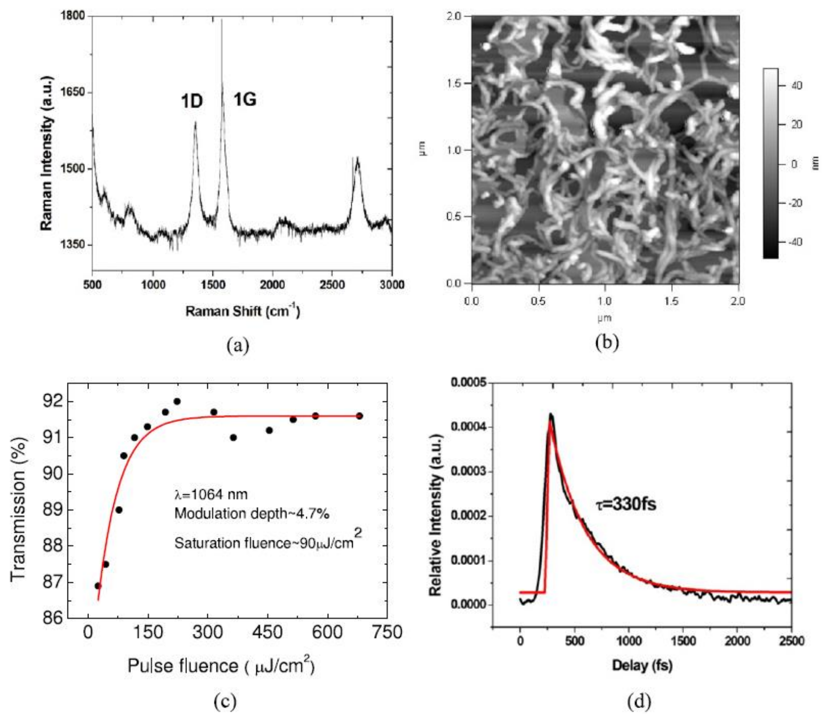

Figure 1. The characteristics of the MWCNT absorber: (a) the Raman spectrum; (b) AFM image; (c) the transmission of the MWCNT absorber versus the input pulse fluence; (d) recovery time.

high power ultrafast laser development. The Young modulus of MWCNT is around 1000 GPa [22] and the thermal conductivity of MWCNT, 3000 W m^{-1} K^{-1}, is very high [23]. Furthermore, MWCNT has less environmental sensitivity than SWCNT, DWCNT because of its multiple-walled structure. These favorable features are due to the structure of MWCNT which takes the form of a stack of concentrically rolled graphene sheets. The outer walls can protect the inner walls from damage or oxidation so that the thermal or laser damage threshold of MWCNT is higher than that of any other carbon nanotube [24, 25].

In this letter, we introduce a novel type of MWCNT absorber, measure its nonlinear parameters, and demonstrate its successful application in a passively mode-locked Nd:YVO_4 laser. Up to 1.4 W output power has been achieved in a passively mode-locked laser with a slope efficiency of 24%. The nonlinear characteristics of the MWCNT absorber were measured in this study. The encouraging results indicate the potential of MWCNT absorbers for high power mode-locking applications.

2. The fabrication and measurement of the absorbers

The MWCNT material used for the fabrication of the absorber in this experiment is functionalized so that it can be dissolved in water. The diameter of the MWCNTs is about 20–40 nm and the length distribution is from 1 to 2 μm. The fabrication procedure of the MWCNT absorber is similar to that of the SWCNT absorber described in [9]. Figure 1(a) shows the Raman spectrum of the MWCNT absorber when it is excited by a 488 nm Ar ion laser. The spectrum reveals the two characteristic peaks 1D and 1G of MWCNT (the 1D peak at 1358 cm^{-1} and the 1G peak at 1582 cm^{-1}). Figure 1(b) shows the AFM image of the absorber. To investigate the characteristics of saturable absorption, the transmittance of the laser in the MWCNT saturable absorber is measured as a function of laser energy density, as shown in figure 1(c). By fitting the absolute transmittance of the MWCNT absorber versus the input pulse fluence, it is found that the saturation starts at a fluence of $\sim$90 μJ cm^{-2}. At this fluence level, the modulation depth of the MWCNT-SA was about 4.7%. The recovery time was measured to be 330 fs as shown in figure 1(d) by using a pump probe setup.

3. Mode-locking operation

Figure 2 illustrates the experimental setup of the dynamically stable mode-locked Nd:YVO_4 laser based on an MWCNT saturable absorber. An 808 nm, 105 μm diameter, 0.22 NA fiber-coupled LD pump source was used in the experiment. The gain medium was a 4 mm × 4 mm × 10 mm a-cut Nd:YVO_4 crystal. The cavity mirrors M_1, M_2, and M_5 were all flat mirrors. The cavity mirrors M_3 and M_4 had radii of

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