Optics and Laser Technology 97 (2017) 84–89

Contents lists available at ScienceDirect

Optics and Laser Technology

journal homepage: www.elsevier.com/locate/optlastec

Full length article

Diode-pumped passively Q-switched Nd:YVO_4 laser using a reticularly ordered single-walled carbon nanotube saturable absorber

Xiaodong Zhang [a], Shengzhi Zhao [a], Ying Li [b], Yan Zhang [b], Dechun Li [a,*], Kejian Yang [a], Xiangyang Li [c], Reng Wang [c]

[a] School of Information Science and Engineering, Shandong University, 27 Shanda South Road, Jinan 250100, China
[b] School of Chemistry and Chemical Engineering, Shandong University, 27 Shanda South Road, Jinan 250100, China
[c] Shanghai Institute of Technical Physics, Chinese Academy of Sciences, Shanghai 200083, China

ARTICLE INFO

Article history:
Received 28 February 2017
Received in revised form 21 June 2017
Accepted 25 June 2017

Keywords:
Lasers
Diode-pumped
Passively Q-switched
Solid-state laser
Single-walled carbon nanotube
Saturable absorber

ABSTRACT

In this letter, we demonstrate a diode-pumped passively Q-switched Nd:YVO_4 laser with reticularly ordered single-walled carbon nanotube as saturable absorber. Stable Q-switched pulses with a pulse energy of 0.322 μJ, a pulse width of 78.7 ns and a pulse repetition rate of 410.3 kHz have been obtained. Compared with the passively Q-switched laser with carbon nanotubes dispersed by sodium dodecyl sulfate (SDS), the laser with reticularly ordered single-walled carbon nanotube can produce shorter pulses and higher peak power at almost the same incident pump power. The results suggest that the reticularly ordered single-walled carbon nanotube can be an attractive candidate of saturable absorber for Q-switched laser.

1. Introduction

Passive Q-switching is an important technology to obtain output laser pulses with high energy and short duration. In recent years, the Q-switched solid-state lasers have been widely applied in the fields of military, information storage, and industrial processing [1–3]. At 1 μm wavelength, passively Q-switched lasers with saturable absorbers, such as GaAs, Cr^{4+}:YSGG, Cr^{4+}:YAG, Cr^{4+}:YSO bulk crystals and semiconductor saturable absorber mirrors (SESAMs), have been reported [4–8]. However, these kinds of saturable absorbers tend to be uncontrollable and they need complex fabrication as well as packaging during the Q-switching operation. As promising alternatives, single-walled carbon nanotubes (SWCNTs) have many merits such as broad wavelength range from 1 to 2 μm, simple fabrication process, low cost, fast recovery time, as well as high speed third-order optical nonlinearity [9]. Therefore, SWCNTs have been successfully employed as saturable absorbers and attracted a lot of attention [10,11], and the Q-switched Nd:YAG laser with SWCNT film, Q-switched Tm,Ho:YAP laser with SWCNT solution and passively Q-switched Nd:GGG laser with SWCNT/PVA have been reported in recent years [12–14].

As a kind of novel optical material, large-scale organized SWCNT arrays have been synthesized [15], in which many interesting optical properties such as photonic crystal effects, directional emission, wavelength-selective emission, and polarization have been observed [16–19]. These optical properties will bring many interesting influences when the SWCNT arrays are employed in Q-switched lasers. However, how to obtain ordered assemblies of individual SWCNTs with exquisite control over the placement and orientation comes to be a tough challenge. Recent years, a large number of studies have focused on the fabrication methods, and ordered SWCNT materials in different forms have been made by various ways, such as SWCNT forests produced by chemical vapor deposition (CVD) [20], self-assembled SWCNT in solution [21], uniaxially stretched polymer/SWCNT composite [22,23], and SWCNT film fabricated by vertical evaporation technique [24]. During the above mentioned fabrication methods, self-assembly is an efficient way to assemble micro-and nano-objects into ordered macroscopic structures [25]. In the self-assembly process, aqueous solution of surfactants can be used for dispersing high concentration of individual SWCNTs, and bring out quite positive progresses [26,27]. SWCNTs with different microscopic order have different nonlinear optical properties, in particular to those who have the increased exploitation of tube-to-tube interactions. However, the non-saturable losses in SWCNTs are only caused by scattering

* Corresponding author.
E-mail address: dechun@sdu.edu.cn (D. Li).

http://dx.doi.org/10.1016/j.optlastec.2017.06.016

and induce sample heating. Bundling may also serve to increase the effects of tube-to-tube interactions, which may accelerate absorber relaxation of SWCNTs. So, the highly ordered structure of SWCNT is a potential candidate to realize better saturable absorber [28].

In this paper, reticularly ordered SWCNT solution is achieved by self-assembly method. We present the performance of a diode-pumped passively Q-switched $Nd:YVO_4$ laser with reticularly ordered SWCNT for the first time. For comparison, the Q-switched $Nd:YVO_4$ laser with traditional SWCNT solution, which is dispersed by surfactant, is also achieved under the same conditions. Moreover, a deeper explanation about the different Q-switched laser performance of SWCNT and reticularly ordered SWCNT is provided.

2. Experiment setup

The SWCNT powders used in our experiments (Catalog Number: 704113) were purchased from SIGMA–ALDRICH Company. The diameter of the SWCNTs is about 1 nm and the length distribution is from 0.5 to 2.5 μm. In our experiments, we successfully accomplished the fabrication of reticularly ordered SWCNT solution. During the fabrication, we used two different methods to process the SWCNT powders.

In the first method, a novel kind of nonionic surfactant N, N-bis (2-hydroxyethyl) dodecanamide (DDA) was used to construct the ordered association structure of the SWCNT powder. The reticularly ordered SWCNTs were formed together with the ordered self-assembly of DDA, which required an aqueous solution environment under mild ultrasonic stirring and evaporation of water might damage the reticularly ordered structure. The extent of self-assembly can be controlled by adjusting the oil/water ratio of the DDA-dodecane-water system. The obtained carbon nanotubes appeared to possess a highly organized network architecture in the dispersion. The transmission electron micrographs (TEM) images are shown in Fig. 1(a). The TEM images reveal that the SWCNTs are presented as individuals, no bundles and ropes are found in the images. And on the other hand, we can see that the SWCNTs are formed to appear as highly organized network architectures with different geometries and various dimensions. Fig. 1(b) is the portion magnification of Fig. 1(a).

The Atomic Force Microscope (AFM) image in Fig. 2(a) shows the microcosmic information about the reticularly ordered structure, from which it can be seen that SWCNTs are combined with each other. The AFM image in Fig. 2(b) indicates that the reticularly ordered structure is formed by SWCNTs and the thickness of this thin layer is about 2 nm.

For comparison, we obtained the SWCNT solution with the sodium dodecyl sulfate (SDS) [29]. Several milligrams of SWCNT powder were poured into 10 ml 0.1% SDS aqueous solution (SDS was used as a surfactant). After the ultrasonic process and centrifugal treatment, SWCNT solution with the concentration of 2.5 mg in 10 ml aqueous solution was obtained.

Both of the two kinds of SWCNT solutions were put into the 2 mm × 10 mm × 45 mm cuvette and operated as saturable absorbers during our experiment. The concentration of the SWCNT solutions by SDS or DDA was 0.25 mg per milliliter.

The absorption spectrum of SWCNT in the DDA-dodecane-water system and SWCNT solution with the SDS were given in Fig. 3. It can be seen that the SWCNTs in DDA solution, which is the reticularly ordered SWCNT, have less absorption losses at 1064 nm than the other sample. The absorption peak of the SWCNTs appears at about 1.2 μm. The lower absorption rate will introduce low unsaturable loss in the laser cavity.

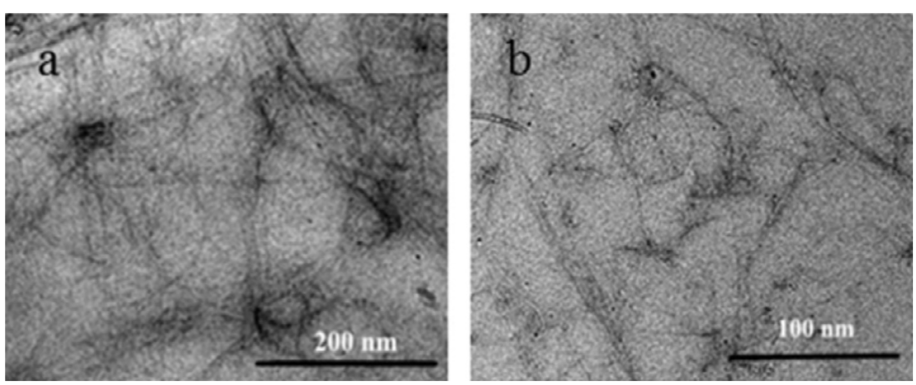

Fig. 1. (a) The transmission electron micrographs of the reticularly ordered SWCNTs aqueous solution. (b) The portion magnification of (a).

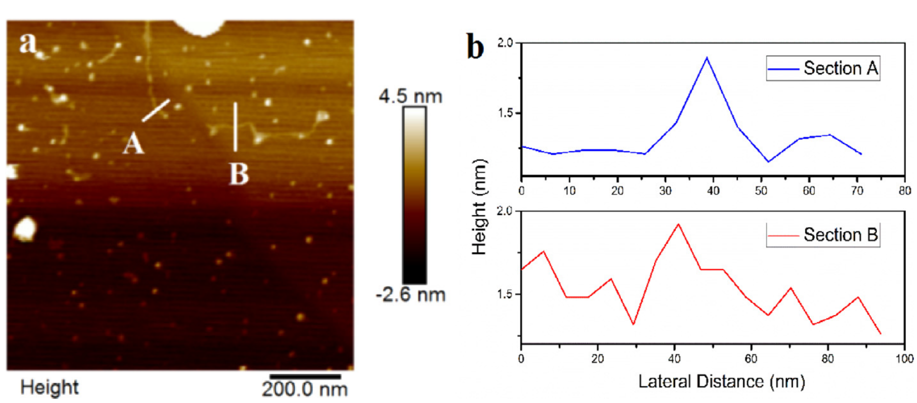

Fig. 2. (a) AFM image. (b). Thickness distribution of the SWCNTs.