Dual-wavelength mode-locked Yb:LuYSiO$_5$ laser with a double-walled carbon nanotube saturable absorber

To cite this article: Q Yang et al 2012 Laser Phys. Lett. 9 135

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Abstract: We report a passively dual-wavelength mode-locked Yb:LuYSiO$_5$ (Yb:LYSO) laser with a double-walled carbon nanotube saturable absorber (DWCNT-SA) for the first time. Simultaneous mode-locking at the 1045.5 and 1059.0 nm was achieved and the pulse duration of the dual-wavelength mode-locked pulses are 8.0 ps. Ultrahigh repetition rate ultrashort pulses with 750 fs pulse width and 3.66 THz repetition rate were further obtained. The average output power of 1.27 W with a repetition rate of 103.5 MHz was obtained using absorbed pump power of 12.83 W and the slope efficiency is 13.0%.

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Received: 19 September 2011, Revised: 29 September 2011, Accepted: 2 October 2011
Published online: 2 December 2011

Key words: dual-wavelength; mode-locked; double-wall carbon nanotube saturable absorber; Yb:LYSO crystal

1. Introduction

Dual-wavelength synchronously mode-locked lasers are attractive for applications like ultrahigh repetition rate pulses and generation of terahertz (THz) radiation. THz waves have a lot of important promising applications, such as propagating certain objects inside atmosphere gases, crystals, organic materials, and so on; investigation and diagnostics of large molecules and molecular chains; Another group of applications is concerned with THz radiovision: communication, radio-astronomy, and aeronomy. For those reasons, applications using THz waves for basic and applied physics, biological, medical, communications, and security are anticipated [1,2].

Previous experimental studies on the dual-wavelength synchronously mode-locked lasers were mainly focused on the Ti:Sapphire laser [3–11]. Mode-locked Ti:Sapphire laser based on self-spectrum splitting, without the imposed blocking of the beam at the dispersive end of the laser. The disadvantage of self-splitting is that the wavelength separation is very small and cannot be changed. Recently, many papers reported the generation of dual wavelength synchronous laser pulses at 1 µm wavelength.
Dual-wavelength continuous wave, passively Q-switched and mode-locked lasers based on Nd-doped disordered crystals, such as Nd:CNGG, Nd:LGGO, and Nd:LYSO have been demonstrated [12–15]. A dual-wavelength synchronously mode-locked Yb:YAG ceramic laser was also reported [16]. A high power dual-wavelength continuous-wave output of master oscillator power amplifier system was achieved at 1053 and 1083 nm [17]. A dual-wavelength passively mode-locked Bi-doped all-fiber ring laser by using nonlinear polarization rotation (NPR) technique was also demonstrated [18].

Carbon nanotubes (CNTs) are one of the most interesting advanced materials in recent years due to their unique electric and optical properties and have been intensively investigated since their discovery. Semiconducting double-walled carbon nanotubes (DWCNTs) turned out to be particularly a promising material for developing ultrafast saturable absorbers for laser mode-locking. While conventional semiconductor saturable absorber mirrors (SESAMs) require sophisticated manufacturing techniques, such as metal-organic chemical vapor deposition, and molecular beam epitaxy, and may have to undergo additional postprocessing for reducing recovery times. DWCNT-based saturable absorbers (DWCNT-SAs) can be manufactured in a much simpler and cost-efficient way with well-known techniques such as spin coating or spray methods. Moreover, DWCNT-SAs exhibit broad spectral range and fast recovery times, high damage threshold comparable to those of SESAMs [19–22]. Recently, many demonstrations of solid-state lasers with carbon based material absorber have proposed [23–26]. Therefore, DWCNT-SAs have potential to take the place of SESAMs in ultrafast solid-state laser mode-locking.

Yb$^{3+}$ doped crystals are highly suitable for use as gain media for ultrafast lasers. Until now, various diode pumped Yb-doped continuous-wave and ultrafast lasers have been demonstrated [27–30]. A promising ytterbium-doped alloyed oxyorthosilicate crystal Yb:LuYSiO$_5$ (Yb:LYSO) exhibits combined advantages of both Yb:LSO and Yb:YSO crystals, such as large ground-state splittings, broad absorption and emission spectra and excellent mechanical property. The tunable and ultrafast performance of the Yb:LYSO were experimentally investigated [31–34]. However, dual-wavelength passively mode-locked of the Yb:LYSO laser has not been reported by far.

In this letter, we report on the dual-wavelength passively mode-locked Yb:LYSO laser with a DWCNT-SA. To our knowledge, it is the first time to achieve dual-wavelength mode-locking with carbon based material absorber. Dual-wavelength mode-locking at 1045.5 and 1059.0 nm were operated simultaneously in one beam. The pulse duration of the mode-locked laser are 8.0 ps. The beat pulse duration has a temporal pattern width of 750 fs and the center frequency difference between the two bands is 3.66 THz. Under the absorbed pump power of 12.83 W, the maximum output power was 1.268 W. The slope efficiency is 13.0%.

![Figure 1](online color at www.lphysics.org) Linear transmission curves of quartz substrate and DWCNT absorber

### 2. The fabrication and characteristics of DWCNT-SA

The DWCNT materials were grown by the catalytic vapor decomposition (CVD) method with the length of 5 to 15 μm and the diameter of 5 nm. At the first step, several milligrams of DWCNT powder were poured into 10 ml 0.1% sodium dodecyl sulfate (SDS) aqueous solution. Here SDS was used as a surfactant. In order to obtain DWCNT aqueous dispersion with high absorption, DWCNT aqueous solution was ultrasonically agitated for 10 hours. After the ultrasonic process, the dispersed solution of DWCNTs was centrifuged to remove sedimentation of large DWCNT bundles. After decanting the upper portion of the centrifuged solution to a bottle, the DWCNTs dispersion was diluted and then poured into a polystyrene cell. Then a hydrophilic quartz substrate was inserted into the cell vertically. The polystyrene cell was put on a table at the atmosphere for gradual evaporation. It took about two weeks to transfer DWCNTs to the substrate.

An UV-Visible-NIR spectrophotometer was employed as shown in Fig. 1 to measure the linear optical transmission of the DWCNT absorber. We can adjust the amount of DWCNT in the dispersion to control the final density of the DWCNTs on the quartz substrate. Fig. 2 shows the Raman spectrum of DWCNT absorber. The laser was excited by 488 nm Ar ion laser. The ratio between the D band and the G band is a good indicator of the quantity on the CNTs. If both bands have similar intensities this would imply a large quantity of structural defects. From Fig. 2 we know the G/D ratio (G peak at 1588 cm$^{-1}$, D peak at 1355 cm$^{-1}$) is as high as 12.5, which indicates that the quality of the crystal is very good.
3. Experimental setup

A schematic setup of the experiment is shown in Fig. 3. A W-type cavity was used to ensure a small spot size on the crystal and carbon nanotube saturable absorber. The alloyed Yb:Lu$_2$(1-x)Y$_2x$SiO$_5$ (x = 0.5) laser crystal was grown by Czochraski method from a 50/50 solution of Lu$_2$SiO$_5$ (LSO) and Y$_2$SiO$_5$ (YSO) in inductively heated iridium crucibles, with the dopant Yb$^{3+}$ of 5 at.\% (with dimension of 3×3×3 mm$^3$). To efficiently remove the generated heat during the experiment, the crystal was wrapped with indium foil and mounted in a water-cooled copper heat sink, and the temperature of the laser crystal was maintained at 14°C to lower the laser threshold. It was pumped by a fiber coupled laser diode (LYPE30-SG-WL980-F400) operating at 977 nm with a fiber core diameter of 400 μm and numerical apertures of 0.22. The input mirror, flat cavity mirror M1 was coated with high transmission at 976 nm and high reflection in a broad band from 1030 to 1080 nm. The concave cavity mirrors M2, M3, and M4 have the radius of curvature 200, 800, and 100 mm and all coated for high reflection in a broad band from 1030 to 1080 nm, respectively. To sustain a high intracavity circulating power, an output coupler with a low transmission of 4% is also coated for high reflection in a broad band from 1030 to 1080 nm. The transmission-type DWCNT-SA used in the experiment was embedded in the cavity next to output coupler. The length between M1 and M2 was about 88 mm. M2 and M3 were separated by 420 mm, while the length between M3 and M4 was about 890 mm, and the separation between M4 and M5 was 53 mm. The total length of the folded cavity was 1451 mm. We can estimate that the beam waists were about 90 μm in the Yb:LYSO crystal and 28 μm on the DWCNT-SA by the ABCD analysis.

![Figure 3](online color at www.lphys.org) Experimental setup for passively mode-locked Yb:LYSO laser

![Figure 4](online color at www.lphys.org) CW and mode-locking average output power versus the absorbed pump power
4. Results and discussion

Without the DWCNT-SA, continuous wave (CW) laser emission was obtained. The corresponding CW output power versus incident pump power curve is shown in Fig. 4. The laser threshold is 2.96 W. The laser produced a maximum average output power of 2.10 W as the pump power of 12.83 W. The slope efficiency of the laser was 13.0%. We note that is difference from previous reports [13,15,16], no dispersion compensation was conducted in the cavity. Stable and synchronized dual-wavelength passively mode-locked pulses were achieved in the laser. We believe it’s due to the small modulation depths of the DWCNT-SA. The saturable absorption of DWCNT-SA could impose an attraction force between the pulses. Although the effect of cavity dispersion is to separate the pulses, the effect of the DWCNT-SA is to tarp them together. Finally, balance of them could be reached, the stable pulses is formed in the cavity.

The CW mode-locked pulse trains under the absorbed pump power 8.77 W shown in Fig. 5 were recorded by a fast photodiode detector (New Focus 1611-AC-FSM) with a rising time of 400 ps and recorded with a 1 GHz digital storage oscilloscope (Tektronix TDS5104). Fig. 5a was recorded with a time scale of 10 ns/div and Fig. 5b was recorded with a time scale of 1 µs/div. The pulse repetition rate was 103.5 MHz. It is in good agreement with the theoretical results, which is given by

\[ f = \frac{c}{2L} \]  

(c is the speed of light and L is total length of the resonator).

The optical spectrum of the mode-locked pulses shown in the Fig. 6 was measured with an optical spectrum analyzer (AvaSpec-3648-USB2). Dual-wavelength mode-locking at 1045.5 and 1059.0 nm were operated simultaneously in one beam. The spectral band centered at 1045.5 nm has a mode-locked full width at half maximum (FWHM) spectral bandwidth of 1.20 nm and the spectral band centered at wavelength 1059.0 nm has a FWHM of 1.00 nm. The spectral intensity ratio of them is about 1:0.7, and the pulse width ratio of the two pulses is about 1:0.83. The center frequency difference between the two bands is 3.66 THz.

The mode-locked pulse duration at the CW mode-locking operation shown in Fig. 7 was measured with an autocorrelator (Femtochrome, FR-103XL). As the two dual-wavelength mode-locked pulses were temporally overlapped, only one mode-locked pulse was observed in the oscilloscope trace. We estimate that the pulse durations of two dual-color pulses are 8.0 ps, assuming a Gaussian pulse shape. On top of the measured autocorrelation trace a certain fine structure is visible. The beat pulses can be regarded as a cosine-like shape in our case. The intensity-modulated output of the laser can be expressed as

\[ I = I_1 + I_2 + 2\sqrt{I_1 I_2} \cos(2\pi \nu t) \]  

where \( I_1 \) and \( I_2 \) are the intensity of each of the pulses, \( \nu \) is the difference fre-
Figure 7 (online color at www.lphys.org) Autocorrelation trace of the Yb:LYSO mode-locked pulses. (a) – in a long time range and (b) – in a short time range

5. Conclusions

We demonstrated a passively dual-wavelength mode-locked Yb:LYSO laser with a double-walled carbon nanotube saturable absorber. Simultaneous mode-locking at the 1045.5 and 1059.0 nm was achieved at its two closely spaced gain spectral bands. Moreover, the two different wavelength mode-locked pulses were found to be synchronized in the laser. Dual-wavelength mode-locked pulses have a pulse width of 8.0 ps, with the repetition rate of 103.5 MHz. On top of the measured autocorrelation trace a certain fine structure is visible. The interference pattern has a pattern repetition rate of 3.66 THz and the beat pulse duration is about 750 fs. Average output power of 1.27 W was obtained at 12.83 W absorbed pump power. The slope efficiency of the mode-locked laser was about 13.0%. To the best of our knowledge, this is the first dual-wavelength mode-locking achieved by a double-walled carbon nanotube saturable absorber.

Acknowledgements

The authors acknowledge support from the National Natural Science Foundation of China (Grants No. 61078032, No. 60908030, and No. 60938001), the Science and Technology Key Projects Plan of Shandong Province (Grant No. 2010GGX10113), and the Science and Technology Projects Plan of Jinan City (Grant No. 201004007).

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