Passively mode-locked 2-μm Tm:YAP laser with a double-wall carbon nanotube absorber*

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We report on a diode-pumped passively continuous wave (cw) mode-locked Tm:YAP laser with a double-wall carbon nanotube (DWCNT) absorber operating at a wavelength of 2023 nm for the first time, to the best our knowledge. The DWCNT absorber is fabricated on a hydrophilic quartz substrate by using the vertical evaporation technique. The output power is as high as 375 mW. A stable pulse train with a repetition rate of 72.26 MHz is generated with a highest single pulse energy of 5.2 μJ.

Keywords: double-wall carbon nanotubes, Tm:YAP, passive mode-locking

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1. Introduction

Ultrafast lasers emitting in a 2-μm eye-safe spectral range are interesting for applications in spectroscopy, remote sensing, photo-medicine, optical communications, and metrology.[1,2] Passive mode-locking can generate much shorter pulses, especially when a saturable absorber is used as the mode-locker, with virtues of simplicity, compactness, and reliability.[3,4] Up to now, picosecond and femotosecond pulses around 2 μm have been successfully demonstrated in Tm-doped or Tm, Ho-co-doped fiber and bulk lasers based on additive pulse mode-locking,[5] saturable absorption mode-locking in strained InGaAs multiple quantum wells (MQWs),[6] and Sb-based semiconductor saturable absorber mirrors (SESAMs),[7] single-wall carbon nanotubes,[8,9] and PbS quantum-dot-doped glass.[10] But picosecond and femotosecond pulses around 2 μm have been little reported for diode-pumped passive mode-locking. Reference [11] reported the first demonstration of a solid-state laser passively mode-locked through the saturable absorption of short-wavelength intersubband transition in a doped quantum well.

Tm:YAP crystal serving as a laser material near the 2-μm band has aroused widespread concern in recent years because it is very important infrared tunable laser crystal. Tm:YAP crystal has a long fluorescence lifetime, high quantum efficiency, and the absorption of thulium tervalent ions near 790 nm, which matches well with the commercially laser diodes. In addition, the emission cross section of thulium in the YAP crystal (5.5×10^{-21} cm^2) is twice as high as that in the YAG crystal (2.2×10^{-21} cm^2).[12] So, Tm:YAP crystal is suitable for laser diode pumping and is a promising material for laser material. In Ref. [13], the first use of InGaAs/GaAs as a saturable absorber in the Q-switching of a diode pumped Tm:YAP laser was demonstrated. In spite of the fact that all the properties of Tm:YAP are promising, so far, few studies on the CW passively mode-locked operation have been performed.

A semiconducting carbon nanotube absorber is a promising material for saturable absorber laser mode-locking. It can be fabricated in a simple and cost-saving way, such as spray, spin coating or horizontal evaporation methods. The vertical evaporation method was used to fabricate single-walled carbon

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nanotube (SWCNT) absorber for 1-μm mode-locking solid-state laser[14,15] and the output power of the pulse laser is as high as 3.6 W.[15] A double-wall carbon nanotube (DWCNT) absorber is a kind of carbon nanotube saturable absorber. The optical spectroscopic properties of the DWCNT were investigated previously.[16,17] However, it was not until recently that a CW mode-locked 2-μm laser with a DWCNT absorber was reported.

In the present paper, we use a DWCNT absorber for a Tm:YAP laser with mode-locked operation at a wavelength of 2023 nm for the first time. The absorber allows mode-locked pulses with a repetition rate of 72.26 MHz in the Tm:YAP laser. The output power is as high as 375 mW with a highest single pulse energy of 5.2 μJ.

2. Growth and characteristics of DWCNT

The DWCNT materials were grown by using the CVD method. Their lengths are in a range from 5 μm to 15 μm and each of them has a diameter of 5 nm.[18,19] 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 h. After the ultrasonic process, the dispersed solution of DWCNTs was centrifuged to remove the sedimentations of large DWCNT bundles. Decanting the upper portion of the centrifuged solution, the dispersed DWCNT in solution was poured into a polystyrene cell, and then a hydrophilic quartz substrate was inserted into the cell vertically. The polystyrene cell was put on a table in normal atmosphere for gradual evaporation. It took about two weeks to transfer DWCNT on the substrate.

A UV-Visible-NIR spectrophotometer was employed to measure the linear optical transmission of the DWCNT absorber as shown in Fig. 1. We can adjust the amount of DWCNT in the dispersion to control the final density of the DWCNTs on the quartz substrate. Figure 2 shows the Raman spectra of the DWCNT absorber. The absorber was excited by a 488-nm Ar ion laser. The ratio between the D band and the G band is a good indicator of the quantity on CNTs. If both bands have similar intensities this would imply a large number of structural defects. From Fig. 2 we know that 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. The peak near the 300 cm^{-1} is the characteristic peak of DWCNT.

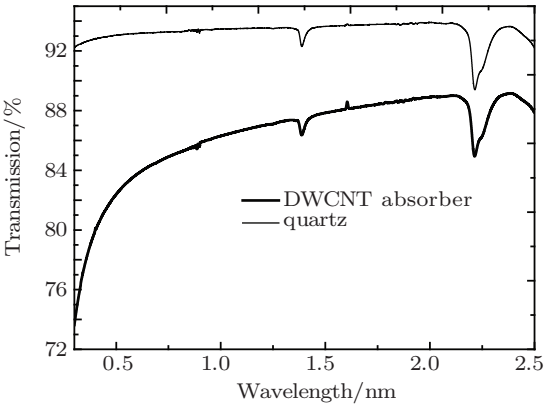


Fig. 1. Linear transmission curves of the quartz substrate and the DWCNT absorber.

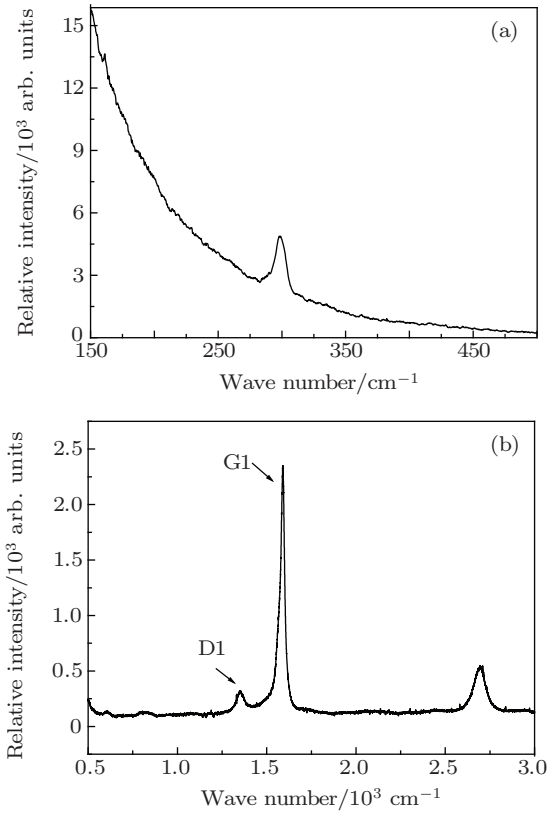


Fig. 2. Raman spectrum intensities of a double-walled carbon nanotube absorber excited by a 488-nm laser: (a) 150 cm^{-1}–500 cm^{-1}, (b) 500 cm^{-1}–3000 cm^{-1}.

3. Mode-locking of a Tm:YAP laser

The experimental setup is shown in Fig. 3. The pump source is a fiber-coupled diode 795-nm laser with a core-diameter of 400 μm and a numerical aperture of 0.22. The pump laser was focused into the Tm:YAP crystal with a radius of 100 μm by using a 1:0.5 focus lens. The laser crystal was a piece of 3 mm×3 mm×5 mm Tm:YAP and the gain medium had a Tm^{3+}-doping concentration of 5%. The crystal had antireflection coating at the pump and laser wavelengths on both its surfaces. It was wrapped in a piece of indium foil and placed within water-cooled housing that was maintained at 17 °C.

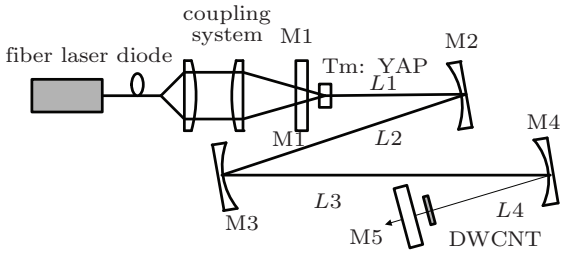


Fig. 3. Schematic configuration of the W-type cavity.

When the intracavity intensity of the laser is low, DWCNT is an effective saturable absorber for Q-switching operation. To generate a mode-locked pulse, the laser intensity must be sufficiently strong. Therefore a cavity is required to have a small beam area in the DWCNT absorber. In addition, optical absorption of pump power can lead to thermal gradients inherently inducing stress and expansion in the laser crystal. Therefore we designed the cavity by using the ABCD matrix theory. According to the ABCD matrix theory, the total length of a W-type-cavity was 2020 mm to ensure the cavity stability through the available pump power and intense focus laser mode with a spot size of 43 μm in radius on the DWCNT. The length of the folded cavity is 2020 mm ($L1$ = 430 mm, $L2$ = 760 mm, $L3$ = 670 mm, $L4$ = 160 mm). The cavity mirror M1 was a flat mirror, which was antireflection coated at 790 nm–810 nm and high-reflection at 1900 nm–2100 nm. The cavity mirrors M2 ($R2$ = 500 mm), M3 ($R3$ = 500 mm), and M4 ($R4$ = 300 mm) were HR-coated at 1900 nm–2100 nm. The output coupler mirror (M5) was a flat mirror and had a transmittance of 2%. The transmission-type DWCNT absorber used in the experiment was located next to M5.

The behaviour of laser average output power as a function of the incident pump power was investigated, and the results are shown in Fig. 4. The lasing oscillation of typical QML threshold was about 2.8 W. When the incident pump power was increased over 4.5 W, the CW mode-locking laser began to operate. At a pump power of 8.64 W, the maximum output power of the CW mode-locked laser was as high as 375 mW with TEM00 mode. The pulse is very stable. Though the diffraction loss is induced by the thermal lens aberration and the reabsorption of Tm ions at high temperature, the laser output power did not exhibit a clear saturation tendency as the pump power was increased. The pulse repetition rate was 72.26 MHz in the laser, it is in good agreement with the theoretical result which is given by $f = c/2l$ (c is the speed of light, l is the optical length of the resonator), and corresponding pulse energy was 5.2 μJ.

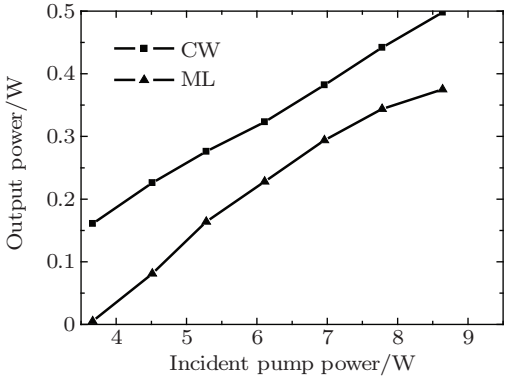


Fig. 4. Variations of the output power with the incident pump power.

Figure 5 shows the pulse train at the CW mode-locked operation detected by a fast photodiode with a rising time of 250 ps (ET-3500) and recorded with a digital storage oscilloscope with 1-GHz bandwidth (Tektronix TDS5104). The inset shows the pulse train recorded in 1 μs per division time scale. The CW mode-locking central wavelength of the Tm:YAP laser was measured to be 2023 nm by using an optical spectrum analyzer (AvaSpec-NIR256-2.5). Figure 6 shows that the spectral bandwidths of the CW operation and the CW mode-locked operation were 19 nm and 23 nm, respectively. We can know that the spectral bandwidth of the CW mode-locked operation was wider than that in the CW operation. Since our autocorrelation apparatus could be applied only to the laser with a wavelength shorter than 1800 nm, we did not measure the profile of autocorrelation signal in this experiment. However, with a digital storage oscilloscope, we can estimate

the width of the pulse from Fig. 5. The formula $t_{\rm real} = \sqrt{(t^2_{\rm measure} - t^2_{\rm probe} - t^2_{\rm oscilloscope})}$ describes the relationship between the real rise time $t_{\rm real}$ of the pulse and the following three parameters, i.e. the measured rise time $t_{\rm measure}$ of the pulse, the rise time $t_{\rm probe}$ of the probe and the rise time $t_{\rm oscilloscope}$ of the oscilloscope employed.[20] Using the above formula, the real rise time of the mode-locked pulse is obtained to be about 33 ps. According to the definition of the rise time and considering the symmetric shape of the mode-locked pulse, we can assume that the width of the pulse is approximately 1.25 times more than the rise time of the pulse. Then the duration of the mode-locked pulse is estimated to be about 41 ps.

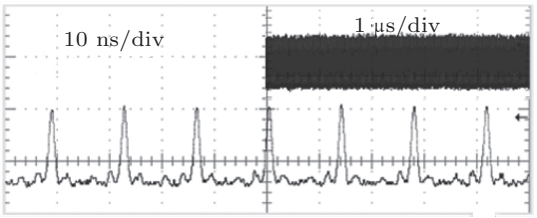


Fig. 5. Pulse train of the CW mode-locked laser with a repetition rate of 72.26 MHz and an average output power of 375 mW recorded in 10 ns per division time scale. The inset shows the pulse train recorded in 1 μs per division time scale.

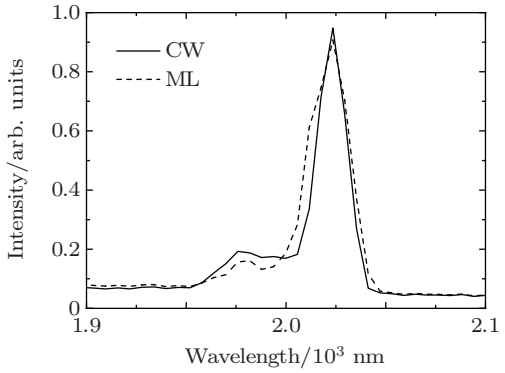


Fig. 6. Emission spectra each with a central wavelength of 2023 nm.

4. Conclusion

In the present paper, we use a vertical evaporation method to fabricate a DWCNT absorber. With the absorber, the mode-locking of a diode-pumped Tm:YAP laser operating at a wavelength of 2023 nm is demonstrated for the first time. With a pump power of 8.64 W, the mode-locked output power reaches as high as 375 mW. The repetition rate and corresponding pulse energy are 72.26 MHz and 5.2 μJ, respectively. These properties indicate that Tm:YAP crystal is an excellent medium for an ultrafast laser. In addition, our experimental results show that the DWCNT is a promising absorber for a 2-μm mode-locking laser.

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