1.34 μm $Nd:YVO_4$ laser mode-locked by a single-walled carbon nanotube saturable absorber

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ABSTRACT

Passive mode-locking of 1.3 μm solid-state lasers is problematic for semiconductor saturable absorber mirrors (SESAMs) not only because of difficulties in their fabrication process but also in relation to the achievable parameters and damage resistivity. In contrast, single-walled carbon nanotube saturable absorbers (SWCNT-SAs) exhibit broadband absorption which is controllable by varying the nanotube diameter and chirality, and require relatively simple manufacturing processes. Here we report on steady-state mode-locked operation of a diode pumped $Nd:YVO_4$ laser on the $^4F_{3/2}\rightarrow{}^4I_{13/2}$ transition at 1.342 μm using a transmitting SWCNT-SA. The SWCNT-SA employed in the present work was fabricated by SWCNTs grown by high-pressure CO conversion technique, showing broad absorption around 1.3 μm. The linear transmission at the laser wavelength was about 99%. The $Nd:YVO_4$ laser was longitudinally pumped by the unpolarized radiation of a 808 nm fiber-coupled laser diode. The ~1.2-m long cavity was optimized for large fundamental mode size. Above threshold the laser operated first in the CW mode, then had a range of Q-switched mode-locked operation before reaching the regime of stable steady-state mode-locking. With an output coupler of 90% reflectivity, the average output power in the steady-state mode-locked regime reached 0.8 W at a slope efficiency of 14.5% with respect to the incident pump power. At a repetition rate of 127 MHz this corresponds to single pulse energy of 6.3 nJ. Such pulse energies are comparable to the best results obtained using SESAMs but the pulse duration of 16.5 ps measured in the present experiment is substantially shorter.

Key words: mode-locked lasers; neodymium lasers; single-walled carbon nanotubes.

1. INTRODUCTION

The near-infrared spectral range around 1.3 μm can be covered by Cr^{4+}-doped forsterite and similar lasers which are characterized by broad tunability and spectral linewidths supporting femtosecond pulse durations, and by Nd-lasers operating on the $^4F_{3/2} \rightarrow {}^4I_{13/2}$ transition which exhibit relatively narrow bandwidths supporting only picosecond pulse durations but are better suited for power scaling under direct diode pumping near 800 nm. Mode-locked lasers of the latter type are interesting for applications in the semiconductor industry, telecommunications and medicine, as well as for frequency doubling to the red spectral range, with all of them profiting from higher average powers. Active mode-locking using amplitude or frequency modulation was the first technique applied to such diode-pumped lasers[1] but it provides in general relatively long pulses if compared to the bandwidth supported by the emission spectrum.

The first passive mode-locking technique applied to diode-pumped 1.3 μm Nd-lasers in the steady-state regime was additive mode-locking.[2] Although this technique is scalable in power,[3] it is a complex and not very practical approach employing single-mode fibers in a coupled cavity and locking electronics.

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The much simpler for realization semiconductor saturable absorber mirror (SESAM) mode-locking is widely used near 1 μm but the spectral region around 1.3 μm is problematic because of difficulties in the fabrication process and damage resistivity. With increasing the operating wavelength, technical and engineering problems occur, generally limiting the optical quality of the SESAMs. In fact, each SESAM is designed and fabricated to operate only at a specific wavelength and it is difficult to optimize its modulation depth independently of the nonsaturable losses. The first demonstration of continuous-wave (CW) SESAM mode-locking of a Nd-laser operating near 1.3 μm was in 1996.[4] In this work, stable mode-locked operation of $Nd:YVO_4$ and Nd:YLF lasers was reported, with relatively low output powers of 50 and 130 mW, respectively. Pulse durations as short as 4.6 ps in the case of $Nd:YVO_4$ and 5.7 ps in the case of Nd:YLF were achieved. Subsequently, few other reports on mode-locked operation of 1.3 μm Nd-lasers by different types of SESAMs appeared, basically trying to improve their performance in terms of average output power and long term stability.[5-7] The highest average output powers (1.05 W at 152 MHz) were demonstrated only recently,[8] with an AlGaInAs based SESAM, however, the pulse duration from this $Nd:YVO_4$ laser amounted to 26.4 ps. More than two times higher average power (2.3 W at 76 MHz) was achieved by reducing the thermal load with in-band pumping at 880 nm,[9] but the pulse duration from this SESAM mode-locked $Nd:YVO_4$ laser was even longer, 29.2 ps.

Also recently, an alternative passive mode-locking technique based on second-order nonlinearity inside the laser cavity which utilizes $\chi^{(2)}$-lens formation in a second-harmonic generation (SHG) crystal assisted by the nonlinear reflection of the so-called Frequency Doubling Nonlinear Mirror (FDNLM), was implemented in a diode-pumped $Nd:YVO_4$ laser operating at 1.342 μm to produce pulses as short as ~4 ps with an average output power of ~1 W.[10,11]

Single-walled carbon nanotube saturable absorbers (SWCNT-SAs), exhibiting broadband absorption, require relatively simple manufacturing processes and their absorption band is controllable by varying the nanotube diameter and chirality. While initial experiments were mainly restricted to mode-locking of fiber lasers which tolerate higher non-saturable losses, recent developments showed universal applicability in bulk solid-state lasers operating in the 1-2 μm spectral range.[12] In particular, the Cr:forsterite laser operating at ~1.25 μm was successfully mode-locked by such SWCNT-SAs, achieving average output powers as high as 295 mW.[12-14]

Previous demonstrations of steady-state passive mode-locking of bulk lasers using SWCNT-SAs included transition metal lasers such as Ti^{3+} and Cr^{4+}, and rare-earth lasers such as Er^{3+}, Yb^{3+}, Tm^{3+}, and Nd^{3+} operating on the 1 μm main transition. Indeed SWCNT-SAs were also applied in $Nd:GdVO_4$ and $Nd:Y_{0.9}Gd_{0.1}VO_4$ lasers operating on the $^4F_{3/2} \rightarrow {}^4I_{13/2}$ transition at 1.34 μm, however, this was in a non-stationary regime with pulsed (lamp) pumping, generating pulses with a duration of 30 ps, grouped in a ~200 ns long train.[15]

In this work we report on steady-state mode-locked operation of a diode pumped $Nd:YVO_4$ laser operating on the $^4F_{3/2} \rightarrow {}^4I_{13/2}$ transition at 1.342 μm using a transmitting SWCNT-SA. The maximum average output power obtained, 0.8 W at a repetition rate of 127 MHz, corresponds to a single pulse energy of 6.3 nJ. The pulse duration achieved in the steady state regime is in the 16.2-16.5 ps range.

2. EXPERIMENTAL SET-UP

The laser cavity employed in the present experiment is shown in Fig. 1. The active element (AE) was a wedged, 9 mm long $Nd:YVO_4$ crystal with 0.3 at. % doping. It was *a*-cut and used for operation in π-polarization. The end faces were antireflection (AR) coated for minimum losses at the laser wavelength. It was mounted in a Cu holder whose temperature was stabilized at 25°C by circulating water. The $Nd:YVO_4$ laser was longitudinally pumped by the unpolarized radiation of a 808 nm laser diode bar coupled into a 400 μm optical fiber (NA=0.22). The output beam from the optical fiber was focused by a 1:1 reimaging unit and delivered onto the $Nd:YVO_4$ crystal with a spot radius of ~200 μm through the highly reflecting plane end mirror M1 which transmits the pump radiation (Fig. 1). The active element absorbs ~92% of the incident pump power, optimized by adjustment of the temperature of the laser diode.

The radius of curvature (RC) of the folding mirror M2, the focal length of the AR-coated intracavity lens (F3), and the separations given in Fig. 1 were chosen in such a way in order to ensure a Gaussian beam radii of ~80 μm on the output coupler (OC) and ~200 μm in the position of the active element. Two plane mirrors with different reflectivity (95% and 90%) were employed as OCs. The cavity length corresponds to a repetition frequency of 127 MHz.

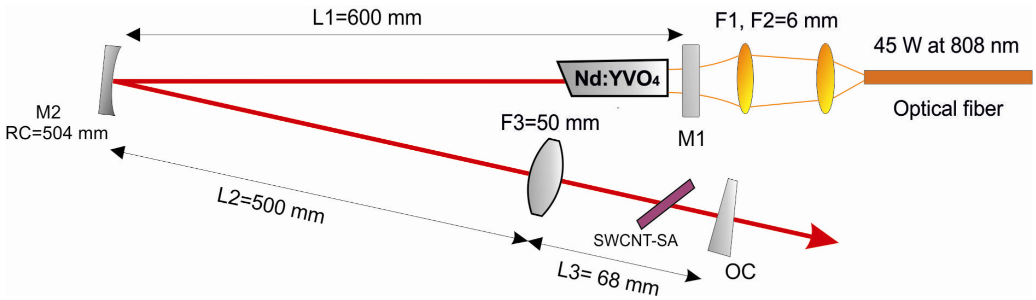

Fig. 1. Schematic of the mode-locked $Nd:YVO_4$ laser cavity: F1, F2 - pump objective, M1, M2 - highly reflecting mirrors, F3 - focusing lens, OC - output coupler.

The SWCNT-SA used in the present work was fabricated by SWCNTs grown by high-pressure CO conversion technique, showing a broad absorption band around 1.3 µm.[12] After dispersing SWCNTs of 0.3 mg/ml in dichlorobenzene (DCB) via ultrasonic agitation, the well-dispersed SWCNTs/DCB solution was mixed with PMMA and spin coated on a quartz substrate. The linear transmission measured near 1.35 µm was about 99%.

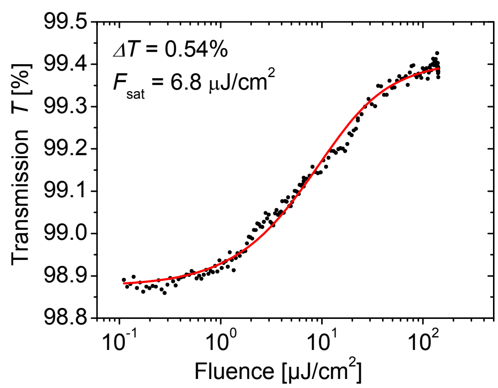

Fig. 2. Nonlinear transmission measurement of the SWCNT-SA with femtosecond pulses at ~1.3 µm.

About half of the losses (0.54%) were saturable and a saturation fluence of 6.8 µJ/cm^2 was measured at 1.3 µm using a femtosecond synchronously pumped optical parametric oscillator at 80 MHz (Fig. 2).

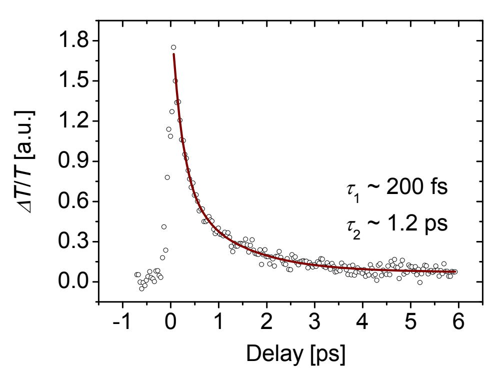

Fig. 3. Pump and probe measurement of the SWCNT-SA with femtosecond pulses at ~1.3 µm from the same source.

A fast (~200 fs, comparable to the time resolution) and a slow (~1.2 ps) component were found for the relaxation time using noncollinear pump and probe technique and the same femtosecond source (Fig. 3). These SA parameters are very similar to the commercial SESAM used in Ref. 9 except for the saturation fluence which is roughly an order of magnitude lower for the SWCNT-SA.

3. EXPERIMENTAL RESULTS AND DISCUSSION

After an initial alignment of the laser, the position of the intracavity lens (F3) and the output coupler (OC) were optimized for maximum output power in the fundamental transverse mode TEM_{00}. Then the SWCNT-SA was inserted close to the output coupler (beam waist) at Brewster angle, in order to minimize the intracavity losses.

Figure 4 shows the measured average output power (black dots) versus the incident pump power and the linear fit (red line) for estimation of the slope efficiency η of the laser with 95% reflecting OC. The laser threshold corresponds to ~1 W of incident pump power while stable steady-state passive mode-locking (ML) is observed in the pump power range between 5.9 and 6.7 W, with maximum average output power of 0.6 W. The slope efficiency of the laser with respect to the incident pump power is η = 10.2%. The autocorrelation function was measured by rotating-mirrors autocorrelator using non-collinear SHG in a $LiIO_3$ nonlinear crystal. The FWHM of the autocorrelation trace, see Fig. 5, is 25 ps which corresponds to a pulse duration (FWHM) of τ = 16.2 ps, assuming $sech^2$ pulse shape.

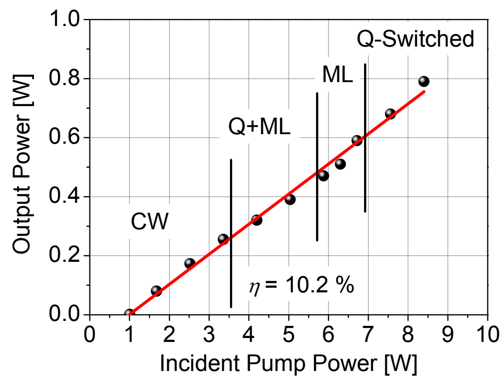

Fig. 4. Input–output characteristics of the SWCNT-SA mode-locked $Nd:YVO_4$ laser using the 95% reflectivity OC.

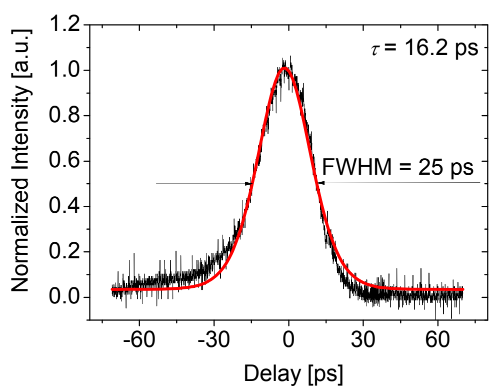

Fig. 5. Recorded autocorrelation trace (black) and fit assuming $sech^2$ pulse shape (red) in the steady-state mode-locked regime of the $Nd:YVO_4$ laser with the 95% reflectivity OC.

Higher average output power and efficiency were possible by optimizing the output coupling, see Fig. 6. Using a mirror with 90% reflectivity at the laser wavelength we were able to increase the average output power in the steady-state mode-locked regime by 33%, up to 0.8 W, corresponding to single pulse energy of 6.3 nJ. The slope efficiency in this case was η = 14.5% with respect to the incident pump power, Fig. 6. The FWHM of the measured autocorrelation trace, see Fig. 7, remained almost unaffected, leading to a pulse duration of τ=16.5 ps under the sech^2 shape assumption.

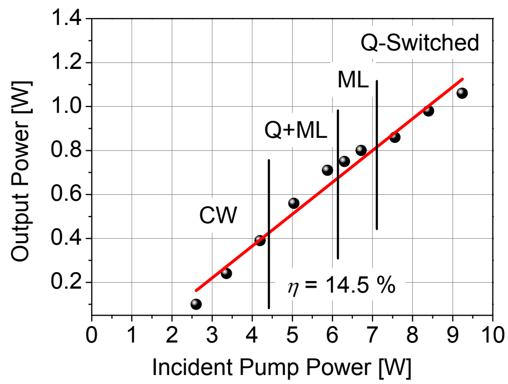

Fig. 6. Input–output characteristics of the SWCNT-SA mode-locked Nd:YVO_4 laser using the 90% reflectivity OC.

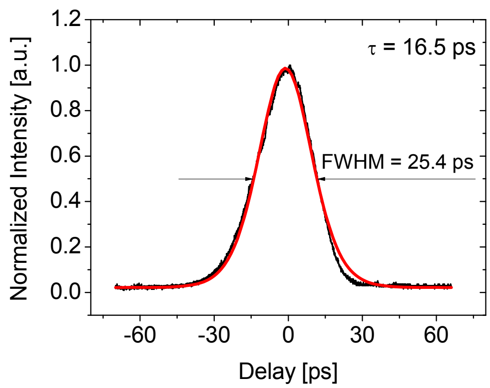

Fig. 7. Recorded autocorrelation trace (black) and fit assuming sech^2 pulse shape (red) in the steady-state mode-locked regime of the Nd:YVO_4 laser with the 95% reflectivity OC.

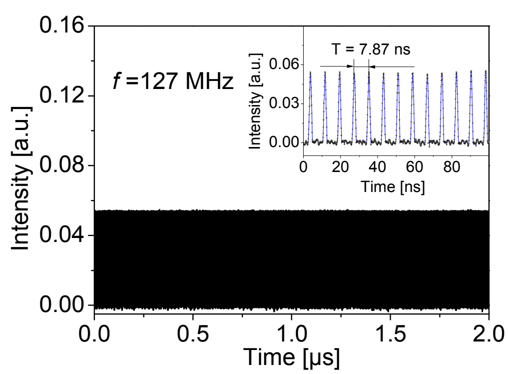

Fig. 8. Oscilloscope trace of the mode-locked laser pulse train using the 90% reflectivity OC recorded by a fast photodiode.

For both OCs used, the laser showed similar behavior with respect to the pump power (see Figs. 4 and 6). Above threshold it operated first in the CW mode, then passed through a range of Q-switched mode-locked (Q+ML) operation before reaching the regime of stable steady-state mode-locking (ML) with the pulse durations mentioned above. Increasing further the pump power resulted in strong Q-switching instabilities and local damage of the SWCNT-SA which limits at present the maximum achievable output power.

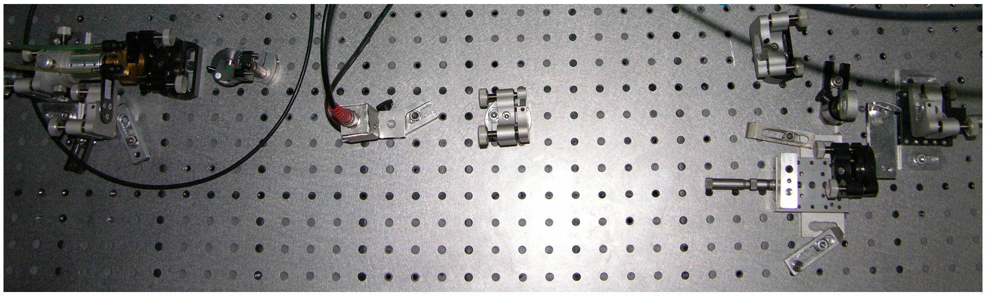

Fig. 9. Photograph of the Nd:YVO_4 laser with the SWCNT SA inside the cavity.

A fast photodiode oscilloscope trace of the laser in the steady state ML regime over a 2 µs period (longer than the time scale for Q-switching and relaxation oscillations) is shown in Fig. 8 together with the individual pulses (inset). No Q-switching instabilities are seen and the amplitude fluctuations are less than 1% on the microsecond time scale.

Finally, Fig. 9 shows a photograph of the Nd:YVO_4 laser with the SWCNT SA inside the laser cavity.

4. CONCLUSION

In conclusion, steady state mode-locked operation of a Nd-laser, Nd:YVO_4, operating on the $^4F_{3/2} \rightarrow {}^4I_{13/2}$ transition around 1.3 µm, is reported for the first time using SWCNT-SA. The maximum average output power obtained, 0.8 W at a repetition rate of 127 MHz, means that in this initial experiment we already achieved the same single pulse energy level as in the most powerful SESAM mode-locked Nd:YVO_4 laser pumped at 808 nm,[8] however, the achieved pulse duration in the present experiment (16.5 ps) is substantially shorter.

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