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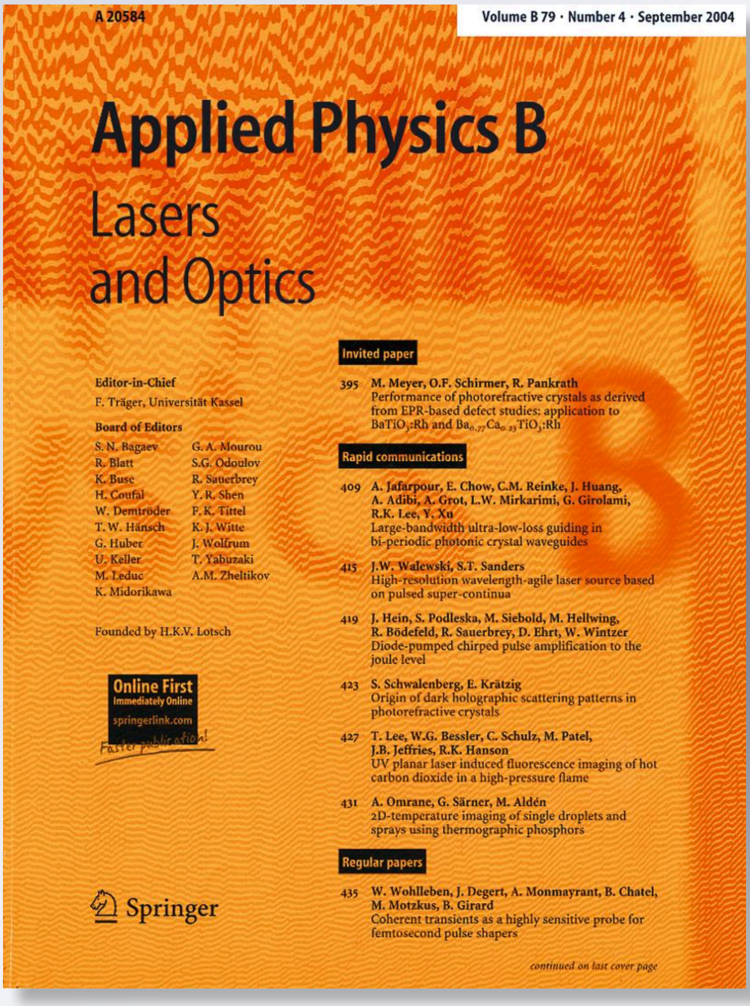

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RAPID COMMUNICATION

Steady state mode-locking of a 1.34 µm Nd:YVO_4 laser using a single-walled carbon nanotube saturable absorber

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Abstract Steady state mode-locked operation of a neodymium laser operating on the $^4F_{3/2} \rightarrow {}^4I_{13/2}$ transition around 1.3 µm is achieved for the first time using transmitting single-walled carbon nanotube (SWCNT) saturable absorber. The Nd:YVO_4 laser cavity was optimized for large fundamental mode volume generating an average power of 0.8 W at a repetition rate of 127 MHz in a stable train of 16.5 ps long pulses.

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. However, passive mode-locking of 1.3 µm 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 at such wavelengths. In general, SESAMs only provide a spectrally narrowband nonlinearity and mandate controlled defect implantation to warrant a suitable response time for ultrashort pulse operation. The first demonstration of continuous-wave (CW) SESAM mode-locking on the $^4F_{3/2} \rightarrow {}^4I_{13/2}$ transition of Nd^{3+} near 1.3 µm was with Nd:YVO_4 and Nd:YLF lasers [1], yielding relatively low output powers of 50 and 130 mW, respectively. The highest average output powers (1.05 W at a repetition rate of 152 MHz) for 808 nm diode pumping were demonstrated only recently with an AlGaInAs based SESAM [2], and the pulse duration from this Nd:YVO_4 laser amounted to 26.4 ps. Pumping at 880 nm to reduce the thermal effects produced an average power of 2.3 W at 76 MHz with SESAM mode-locking, again using Nd:YVO_4, but the pulse duration was still 29.2 ps [3]. It should be noted that the highest average power (4.7 W) and shortest pulse durations (7 ps in this case) from a passively mode-locked 1.3 µm laser (Nd:YVO_4 at 160 MHz) were obtained by additive mode-locking [4], a technique which is scalable in power but represents a rather complex and not very practical approach employing single-mode fibers in a coupled cavity and locking electronics.

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 re-

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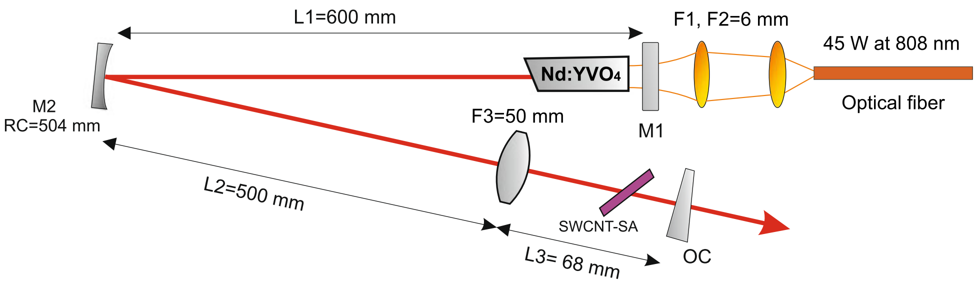

Fig. 1 Experimental set-up of the mode-locked Nd:YVO_4 laser

stricted to mode-locking of fiber lasers which tolerate higher nonsaturable losses, recent developments showed universal applicability in bulk solid-state lasers operating in the 1–2 µm spectral range [5]. In particular, the Cr:forsterite laser operating at ∼1.25 µm was successfully mode-locked by such a SWCNT-SA, achieving average output powers as high as 230 mW [5, 6].

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 nonstationary regime with pulsed (lamp) pumping, generating pulses with a duration of 30 ps, grouped in a ∼200 ns long train [7].

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 setup

The laser cavity used 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 pump power absorption of the AE is ∼92%, 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.

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 [5]. 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 at the laser wavelength near 1.35 µm was about 99%. 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. A fast (∼200 fs, comparable to the time resolution) and a slow (∼1.2 ps) component were found for the relaxation time using noncollinear pimp and probe technique and the same femtosecond source. These SA parameters are very similar to the commercial SESAM used in [3] except for the saturation fluence which is roughly an order of magnitude lower for the SWCNT-SA.

3 Results and discussion

After an initial alignment of the laser, the position of the intracavity lens (F3) and the output coupler 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 2(a) 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

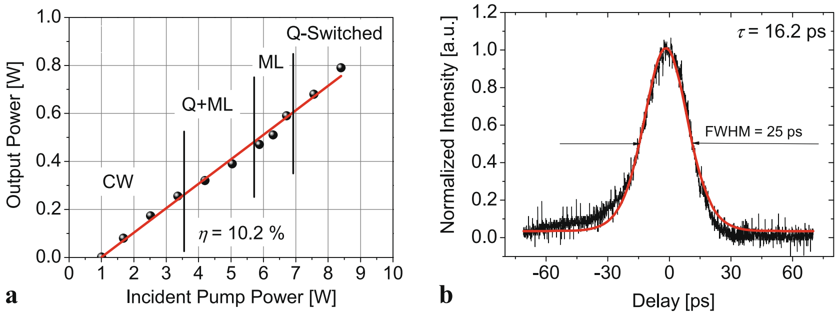

Fig. 2 (**a**) Input–output characteristics of the SWCNT-SA mode-locked Nd:YVO$_4$ laser using the 95% reflectivity OC, and (**b**) recorded autocorrelation trace (*black*) and fit assuming sech^2 pulse shape (*red*) in the steady-state mode-locked regime

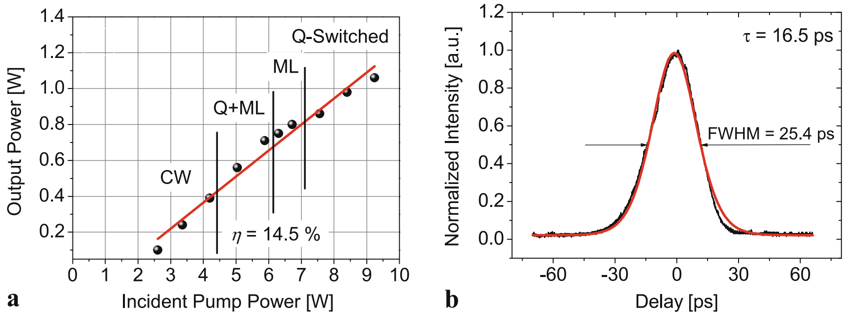

Fig. 3 (**a**) Input–output characteristics of the SWCNT-SA mode-locked Nd:YVO$_4$ laser using the 90% reflectivity OC, and (**b**) recorded autocorrelation trace (*black*) and fit assuming sech^2 pulse shape (*red*) in the steady-state mode-locked regime

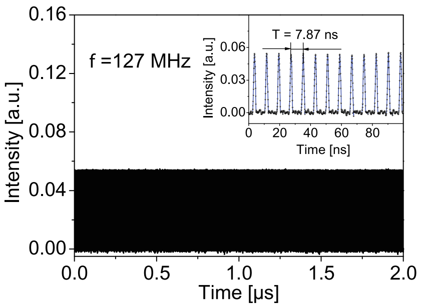

Fig. 4 Oscilloscope trace of the mode-locked laser pulse train using the 90% reflectivity OC recorded by a fast photodiode

of the laser with respect to the incident pump power is $\eta = 10.2\%$. The autocorrelation function was measured by rotating-mirrors autocorrelator using noncollinear second-harmonic generation. The FWHM of the autocorrelation trace (see Fig. 2(b)) is 25 ps, which corresponds to a pulse duration (FWHM) of $\tau = 16.2$ ps, assuming sech^2 pulse shape.

Increasing the output coupling using the mirror with 90% reflectivity at the laser wavelength, it was possible to increase the average output power in the steady state mode-locking regime to 0.8 W at a slope efficiency of $\eta = 14.5\%$ with respect to the incident pump power; see Fig. 3(a). This corresponds to a single pulse energy of 6.3 nJ. The pulse duration remained almost unaffected, Fig. 3(b), with $\tau = 16.5$ ps.

For both OCs used, the laser showed similar behavior with respect to the pump power. 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. A fast photodiode oscilloscope trace of the laser in the steady state ML regime is shown in Fig. 4 over a 2 μs time scale together with the individual pulses. The amplitude fluctuations are less than 1% on the microsecond time scale.

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 [2], however, the corresponding pulse duration in the present experiment (16.5 ps) is substantially shorter.

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