



Multi-Watt Nd:YVO₄ laser, mode locked by a semiconductor saturable absorber mirror and side-pumped by a diode-laser bar

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Abstract

We report on a side-pumped and passively mode-locked all-solid-state laser. The laser consists of an astigmatically compensated resonator with a saturable Bragg reflector to achieve mode locking and a Brewster-cut Nd:YVO₄ rod, which is side-pumped by a diode-laser bar. At 17 W of pump power a fundamental-mode average output power of 4.4 W is attained. The pulse duration was 33 ps as measured at pulse repetition rates of 235 and 440 MHz. © 1999 Elsevier Science B.V. All rights reserved.

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1. Introduction

Currently, a significant amount of interest is concentrated on passive mode-locking of Nd³⁺-lasers with semiconductor saturable absorber mirrors (SESAMs) [1], leading to the generation of pulses in the picosecond and femtosecond regimes but with average powers that have been generally limited to a few hundred milli-Watts by cavity configuration issues and concerns over thermal damage to the saturable absorbers. However, in many applications, such as material processing, achieving higher average power than this is of great importance, even if it involves some small compromise in pulsewidth over the minimum achievable. Reports on multi-Watt all-solid-state passively mode-locked lasers are still rather scarce, giving few details, and usually concentrate on diode-laser end-pumped Nd:YVO₄ [2–4] due to its high gain and excellent efficiency. Here, we report on a Nd:YVO₄ laser side-pumped by a diode-laser bar and mode-locked by a semiconductor Saturable Bragg Reflector (SBR). At 17 W of pump power, a fundamental-mode average power output of

4.4 W was obtained with a pulse duration of 33 ps, and with no evidence of damage to the saturable absorber mirror. Our results demonstrate the suitability of SBRs for achieving multi-Watt average-power mode-locked operation, in a cavity geometry offering promise for even higher power scaling.

Our approach follows from a consideration of factors concerning choice of Nd host medium, choice of cavity and pumping geometry, and design of SESAM, for multi-Watt output power. Side-pumping is a natural route to consider for power scaling, because it is straightforward, comparatively inexpensive, and avoids limitations in delivery of high pump power and thermal problems encountered in end-pumping. As shown below, this leads to the choice of Nd:YVO₄ as a preferred gain medium. Thermally-induced damage to the SESAM is the other main consideration, and we have chosen an SBR-type structure specifically to minimise this effect.

2. Design considerations and setup

A major problem with solid-state lasers that are mode-locked with saturable semiconductor absorbers is the pre-

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vention of Q-switching caused by relaxation oscillations. The condition for the absence of these oscillations is given by [5,6]:

$$P \left| \frac{dq}{dP} \right| < \frac{g_0}{g} \frac{T_R}{\tau}, \quad (1)$$

where P is the power in the cavity, T_R is the cavity round trip time, τ is the fluorescence decay time of the gain medium, q is the saturable loss per round trip, g_0 is the small-signal gain per round trip, and g is the saturated gain per round trip, which at steady state equals the round trip losses of the cavity. As in Ref. [6], the quantities in Eq. (1) are not normalised to the round-trip losses. According to Eq. (1), a high small-signal gain with a short life time of the upper laser level in a long cavity with low losses is favourable for stable cw mode locking. The special properties of Nd:YVO₄ in comparison to other Nd host media, namely very high cross-section for stimulated emission (≈ 5 times larger than Nd:YAG), a comparatively short life time of the upper laser level (98 μ s) and a strong and broad absorption at 809 nm which is very suitable for diode-laser pumping [2,7–9], are very much suited to the fulfilment of Eq. (1). Due to these properties, the use of Nd:YVO₄ allows for higher output coupling (leading to higher efficiencies), shorter cavities, and even side pumping by diode-laser bars [10], therefore being our chosen medium for a power-scalable system.

The astigmatically compensated resonators used in the experiments are shown in Fig. 1. The round-trip time of the resonator in Fig. 1a was 4.26 ns leading to a pulse repetition rate of 235 MHz; for the resonator in Fig. 1b the

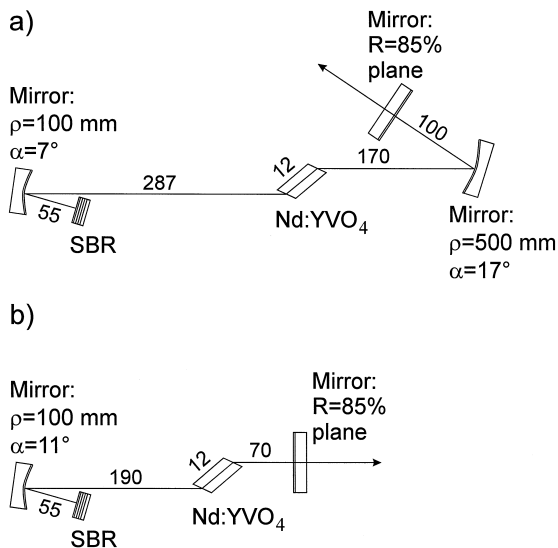


Fig. 1. The resonators that were used in the experiments. The distances are given in mm. R is the reflectivity, ρ the radius of curvature and α the angle of incidence at the corresponding mirror. SBR is the saturable Bragg reflector.

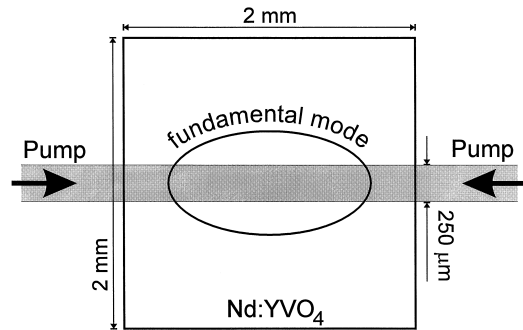


Fig. 2. Cross-sectional view of the side-pumped crystal. The aperture of the crystal and the extent of the pumped region ensure fundamental-mode operation.

round-trip time was 2.27 ns (440 MHz). The 12-mm-long Nd:YVO₄ crystal was Brewster-cut, with its optical axis (c -axis) normal to the sagittal plane in order to exploit the high gain cross-section and the lower thermal lensing of the extraordinary beam. The crystal was side pumped with a fast-axis collimated diode-laser bar (OPC-A020-809-CS/L). As shown in Fig. 2, this set-up was used to ensure pure fundamental-mode operation. Fig. 2 shows the square cross-section of the side-pumped Nd:YVO₄ crystal. The sides are 2 mm wide. The top and bottom crystal faces were covered with indium foil and clamped in a water-cooled copper mount. The pumping diode-laser was placed next to one side of the crystal, the pump radiation being launched through the crystal in the tangential plane along the optical axis. With this orientation, the pump radiation experiences the lower absorption (ordinary beam). The radiation that is not absorbed during the first pass through the crystal is reflected at a curved mirror and is absorbed at its second pass. The mirror used had a radius of curvature of 75 mm and was placed at a distance of 75 mm from the crystal.

With this configuration, the crystal is pumped in a thin layer of about 250 μ m in the tangential plane and cooled normal to it, almost completely avoiding a temperature gradient in the tangential plane so that the thermal lensing has only to be considered in the sagittal plane. At a pump power of 17 W, the thermal lens in the sagittal plane was found to have a focal length of 530 cm. This thermal lens was taken into consideration in the calculation of the eigenmode of the laser resonator using the ABCD-matrix method. For the transitions into and out of the crystal, the matrices derived in Ref. [11] were applied. For both resonators shown in Fig. 1, the astigmatism was compensated for at 17 W of pump power such that the output beam was circularly symmetric. As shown in Fig. 2, the resonator was chosen such that, due to the extent of the TEM₀₀ mode in the crystal, fundamental mode operation was selected by the aperture of the crystal and by the gain of the narrow pumped region in the tangential and sagittal

plane, respectively. In the cavity shown in Fig. 1a, the mode diameters at the centre of the crystal were $1.27 \text{ mm} \times 606 \text{ }\mu\text{m}$ and the mode radii at the saturable Bragg reflector are $33 \text{ }\mu\text{m}$ in the tangential and $47 \text{ }\mu\text{m}$ in the sagittal plane. In the other cavity, the diameters in the crystal were $1.21 \text{ mm} \times 558 \text{ }\mu\text{m}$ and the radii at the SBR are 44 and $60 \text{ }\mu\text{m}$ in the tangential and sagittal plane, respectively.

The SBR [12] that we have designed, consisting of a single $10\text{-nm In}_{0.25}\text{Ga}_{0.75}\text{As}$ quantum well in an AlGaAs Bragg mirror structure [13], was grown by metal-organic chemical vapour deposition at normal growth temperatures for these alloys, which leads to very low non-saturable losses. No thermal damage was observed on these samples up to power densities of several times those reported here. We speculate that the close proximity of the quantum well to the surface in SBR structures may lead to a rapid absorption recovery without the use of low temperature growth or ion implantation (which may introduce additional non-saturable loss) generally required in other types of SESAM [1]. The SBR used was originally designed to mode-lock a Nd:YLF laser on the 1047-nm transition, where a pulse duration as short as 5.7 ps was achieved in an end-pumped geometry [13].

3. Experimental results

At 17 W of pump power in the Nd:YVO₄ laser, an average output power of 4.4 W was attained. Fundamental-mode operation was confirmed by recording the beam waist and the far-field characteristics with a CCD camera. The pulse duration was measured with a non-collinear second-harmonic-generation autocorrelator. Assuming sech^2 pulses, the pulse duration was found to be 33 ps (see Fig. 3a). The pulse spectrum was measured with a home-made scanning Fabry–Perot interferometer, showing that the pulses are about 1.5 times time-bandwidth limited – which is common in semiconductor saturable absorber mode-locked solid-state lasers. This pulse duration is entirely adequate for many applications in the ultrafast regime and, in fact, has some advantages for particular applications (e.g., cavity-length tolerances) such as pumping of optical parametric oscillators. However, it is somewhat longer than the $3\text{--}10 \text{ ps}$ usually achieved for (lower power) passively mode-locked Nd-based lasers. This issue is currently the subject of further investigation, but is considered to involve spatial hole burning due to the gain being positioned away from the end of the cavity [14], and the limited modulation depth and specific temporal absorption-recovery characteristic of the SBR operated at a wavelength far from resonance with the quantum well exciton absorption peak [12].

Mode-locking was found to be very stable and was achieved for output powers exceeding 2 W . At output

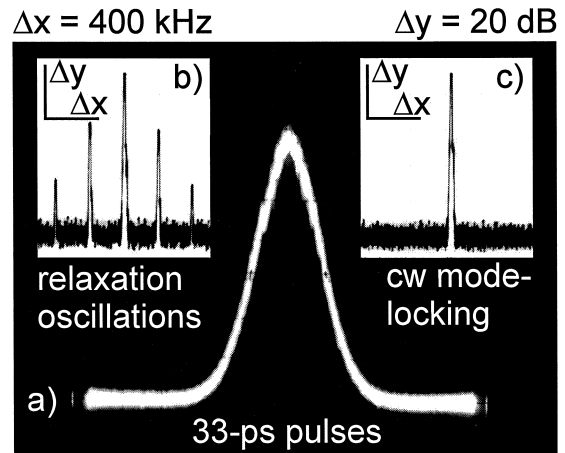


Fig. 3. (a) Autocorrelation of the 33-ps pulses. The power spectra in the insets (b) and (c) show the transition at about 2 W of output power from the relaxation oscillations (b) to pure cw mode-locking (c). The centre peak is the mode-locking frequency at 235 MHz . The resolution bandwidth is 3 kHz . The bars labeled Δx and Δy show the scale of the insets.

powers below 2 W , the modelocked pulse train was modulated at a frequency consistent with the relaxation oscillation frequency. The inset to Fig. 3 indicates the power spectra associated with the relaxation oscillation driven self-Q-switching state (Fig. 3b) and with the quiet pure mode-locked state (Fig. 3c) achieved for output powers greater than 2 W . Note that the strong sideband suppression in Fig. 3c is $> 60 \text{ dB}$. These results were first found using the cavity shown in Fig. 1a. The cavity shown in Fig. 1b was set up in order to test the SBR at a higher repetition rate. Except for the repetition rate, and hence the peak power, the same results as for the longer cavity were obtained.

4. Conclusions and outlook

We have demonstrated a passively mode-locked Nd laser, side-pumped by a diode-laser bar, operating in the multi-Watt output power range. Stable pure cw mode-locking was achieved with output powers ranging from 2 to 4.4 W . The resonators were astigmatically compensated for a pump power of 17 W where 4.4 W of output power with 33-ps pulses were attained. This laser will be used to synchronously pump an optical parametric oscillator with a 50 mm long periodically poled lithium niobate crystal oscillating at a signal wavelength around 1560 nm . A pump depletion exceeding 47% has been attained in preliminary experiments. Using two diode laser bars to pump the Nd:YVO₄ laser indicate power scaling of this mode-locked laser to at least 6.7 W , which will be reported on more fully at a later date.

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