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High-peak-power diode-pumped passively Q-switched Nd:YVO_4 laser

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ABSTRACT We report on a passively Q-switched diode-pumped Nd:YVO_4 laser polarized along the *a* axis (corresponding to the smallest value of emission cross section at 1064 nm), generating 157-µJ pulses with 6.0-ns time duration (> 20 kW peak power) and 3.6 W of average power at 1064 nm with good beam quality ($M^2 < 1.4$). The selection of the polarization was performed by a novel technique relying on the birefringence of the laser crystal and on the misalignment sensitivity of the resonator.

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1 Introduction

Passively Q-switched (PQS) diode-pumped lasers have attracted significant interest in the last few years because of their inherent simplicity, low cost and reliable operation. Microchip [1, 2] and in general low-pulse-energy PQS lasers [3] have already found their way into the market for a variety of applications including micromachining and range finding. Up-scaling to higher pulse energy and average power has also been demonstrated [4–6]. Owing to their excellent optical quality and cost-effective mass production, Nd:YAG and *a*-cut Nd:YVO_4 have been the preferred laser crystals for high-peak-power and high-average-power PQS lasers, respectively. Other laser materials have been proposed and investigated as potential new hosts in PQS lasers, such as Nd:$GdVO_4$ among the most promising [7]. Vanadate crystals are especially attractive owing to their high optical pumping efficiency (exceeding 50%) and a naturally polarized emission, which avoids the thermally induced birefringence [8] affecting isotropic hosts like Nd:YAG. This is particularly important when high beam quality is necessary, for example when non-linear frequency conversion is required. Both Nd:YVO_4 and Nd:$GdVO_4$ are uniaxial crystals, usually *a*-cut to make the extraordinary wave (polarized parallel to the *c* axis) available for high-efficiency, low-threshold cw diode-pumped lasers. Indeed, the ordinary wave (*a*-polarization) in Nd:YVO_4 has a 3.6-times lower emission cross section [9]. Recently, a comparison of low-power PQS lasers employing either *a*-cut or *c*-cut Nd:YVO_4 crystals was reported [9]. It was shown that *a*-polarized Nd:YVO_4 is more suitable for PQS operation with solid-state Cr:YAG saturable absorbers, since the threshold condition for passive Q-switching can be met in simple resonators not requiring tight focusing in the saturable absorber. Furthermore, since the saturation fluence of the laser transition is inversely proportional to the emission cross section [8], Q-switched pulses with higher energy can be generated by selecting the *a*-polarization.

However, we also note that in *a*-cut crystals one can select the ordinary polarization to optimize PQS, with the additional advantage of exploiting the high absorption efficiency of the pump radiation polarized along the *c* axis.

2 Experiment and discussion

We employed a 50-W fiber-coupled diode laser (Bright Solutions S.r.l., proprietary fiber-coupling technology) emitting at 808 nm central wavelength as the pump source for the PQS laser. The numerical aperture of the $D = 0.4$ mm fiber core diameter was 0.22. The fiber output was imaged 1 : 1 into a 0.5%-doped $4 \times 4 \times 7\ \text{mm}^3$ *a*-cut Nd:YVO_4 crystal (Fig. 1). The laser crystal was coated for high reflectivity at 1064 nm and high transmissivity at 808 nm on one facet, normal to the crystal axis. The second facet was antireflection coated at 1064 nm and it was oriented at an angle $\theta_w = 1°$ with respect to the other. The cavity was kept stable owing to the pump-induced thermal lens, the focal length for which we estimated $f_{\text{th}} \approx 10$ cm at the maximum absorbed pump power

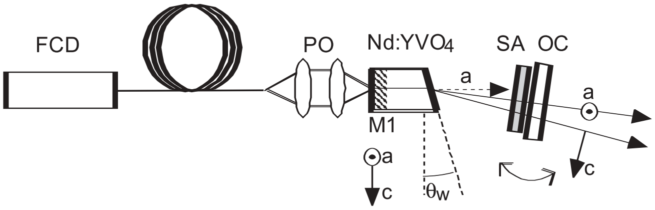

FIGURE 1 Resonator layout. FCD, fiber-coupled diode array; PO, pump focusing optics; M1, pump (rear) mirror; SA, Cr:YAG saturable absorber; OC, output coupler

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✉ Fax: +39-382/422583, E-mail: agnesi@ele.unipv.it used in these experiments (≈ 21.5 W for safe operation of the 0.5%-doped vanadate crystal [10]).

Although the selection of a linear polarization state through an intracavity Brewster-angle polarizer is always possible, its use can be problematic in extremely compact resonators, or its residual loss can be unacceptably high when using extremely low-gain media or in intracavity doubled lasers. Very short resonators can be interesting for the generation of few-nanosecond or even sub-nanosecond pulses in PQS lasers.

Given the simple (plane–plane) resonator set-up, we managed to exploit the crystal birefringence in combination with the misalignment sensitivity of the laser cavity to select the polarization state with the lowest gain. Indeed, the refractive indices corresponding to the orthogonal polarization states in Nd:$\mathrm{YVO_4}$ are $n_a = 1.9573$ and $n_c = 2.1652$ at 1064 nm, allowing an angular separation $(n_c - n_a)\theta_w \approx 3.63$ mrad for the two waves external to the wedged crystal. The misalignment tolerance of the resonator, corresponding to a lateral displacement $D/2$ of the cavity mode with respect to the pump axis, was estimated to be $D/(2f_{\text{th}}) \approx 2$ mrad [8]; therefore, we could switch between the two polarization states simply changing the orientation of the output coupler (Fig. 2).

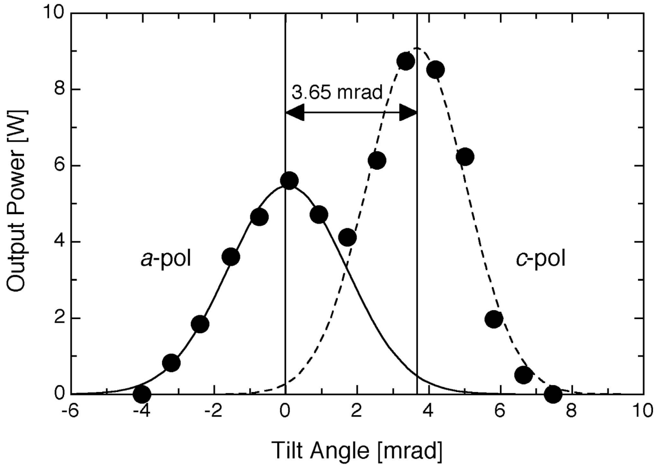

FIGURE 2 Angular tuning characterization for both polarizations (cw). The resonator length was 70 mm, OC reflectivity $R = 80\%$

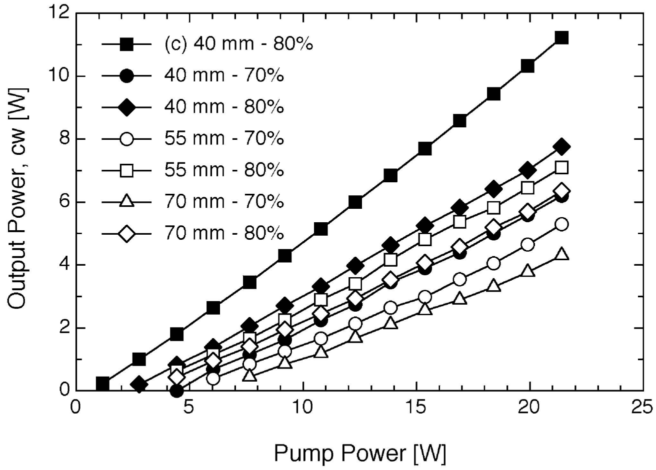

FIGURE 3 Performance of the cw laser. The *upper curve* corresponds to operation with the *c*-polarization and serves for comparison. For each curve the resonator length (mm) and the OC reflectivity (%) are indicated

We investigated first the cw performance for cavity lengths of 40, 55 and 70 mm and with output couplers with reflectivity $R = 70\%$ and 80% (the optimum output coupling for the *c*-polarization has an intermediate value). The results are summarized in Fig. 3, where the *c*-polarization performance serves for comparison. The ratio of the threshold pump power for the two polarizations in the same cavity configuration (upper two curves), approximately 3.5 : 1, agrees with the reported values for the emission cross sections [9]. This also suggests that the *a*-polarization required a higher optimum output coupler reflectivity of approximately 90% [8]. However, the optimum coupling for the PQS laser is generally higher than for cw operation, especially when high-energy pulses at relatively low repetition rates are desired. Another striking feature of Fig. 3 is the fast decrease in the output power with increasing cavity length, even with relatively short resonators. This is due to the larger impact that the thermally induced diffractive loss has on the small-gain *a*-polarization, compared to *c*-polarization: considering the thermo-mechanical sensitivity including both the refractive index thermal change and the contribution of thermal expansion ($\nu \approx 0.33$ is the Poisson ratio), $\chi = \partial n/\partial T + \alpha_T(1+\nu)n$ [11], one finds $\chi_a = \partial n_a/\partial T + \alpha_T^{(a)}(1+\nu)n_a \approx 17.2 \times 10^{-6}\,\mathrm{K}^{-1}$ and $\chi_c = \partial n_c/\partial T + \alpha_T^{(a)}(1+\nu)n_c \approx 12.6 \times 10^{-6}\,\mathrm{K}^{-1}$ [12]. Diffractive losses increase with the resonator length owing to the increased radius of the resonant mode, which experiences larger aberrations in the laser crystal [13]. Furthermore, thermal lensing on the *a*-polarization, which also depends on χ, is stronger: we found that the laser polarization switched from *a* to *c* when the resonator length exceeded the thermal focal length corresponding to the *a*-polarization, thus becoming unstable for this polarization.

We used two Cr:YAG samples as the passive Q-switch, with initial (low-signal) transmissions of 90% and 80%. Below a critical cavity length the PQS operation was not satisfactory, as satellite pulses introduced considerable frequency jitter and strong amplitude fluctuations of the main pulse. This can be understood by the perturbation introduced, in short stable resonators, by higher-order spatial modes with effective radii smaller than the pump spot size, which compete with the $\mathrm{TEM_{00}}$ through complex dynamics involving gain depletion and saturable absorption [14]. However, an optimum cavity length can easily be found trading off the high average power produced by noisy, short resonators, and low-noise operation corresponding to reduced average power (in longer resonators). The optimum cavity length found experimentally according to this criterion was approximately 40 mm. The results obtained are summarized in Fig. 4. It can be seen that both Cr:YAG samples lead to comparable results for the maximum pump power: approximately 145–157 μJ of pulse energy, 3.6–3.8 W average power and a pulse width as low as 6.0 ns (see Fig. 5) for the 80%-transmission Cr:YAG. It is worth noting that for all the configurations considered in Fig. 4, the PQS performance in terms of pulse energy and peak intensity improves by increasing the pump power, owing to the stronger thermal lensing allowing more focusing in the saturable absorber and more effective spatial filtering in

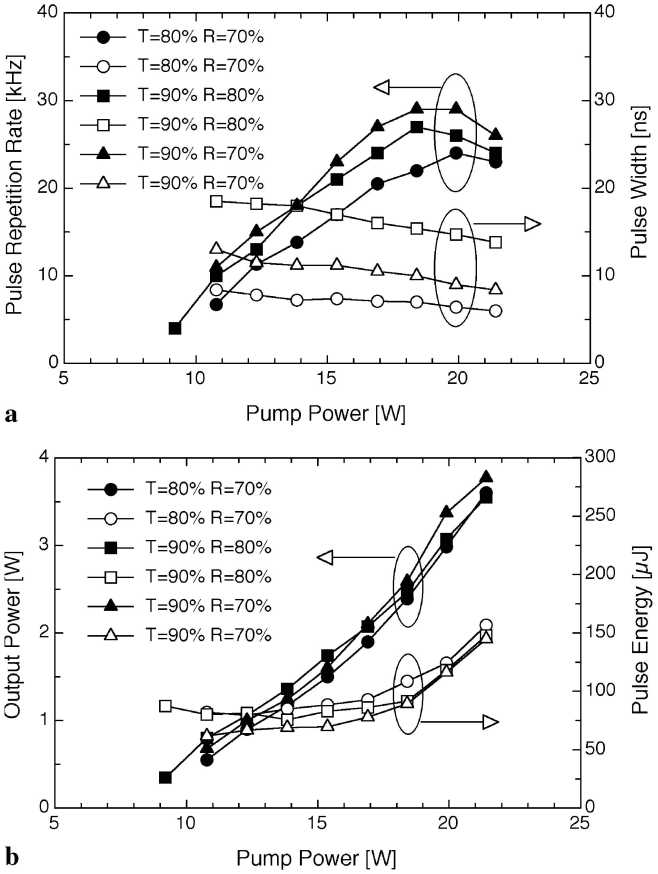

FIGURE 4 Summary of PQS performances. For each curve the Cr:YAG small-signal transmissivity and the OC reflectivity are indicated

the laser crystal. The output beam had a good beam quality ($M^2 < 1.4$) and the pulse amplitude fluctuations and timing jitter were < 2% (rms). The conversion of the cw average power output at 1064 nm to PQS operation, for the given resonator length, is approximately 50%, in agreement with most published results [4–6].

The overall performance might be improved by adding a focusing optics in the resonator [5] (preferably a concave rear mirror to preserve its compactness), such that the spatial mode selection can be done with shorter, intrinsically stable resonators, and with correspondingly lower diffractive losses. This would also allow a more favorable mode area ratio between the laser crystal and saturable absorber, leading to higher peak and average powers, as well as to a PQS operation less sensitive to thermal lensing.

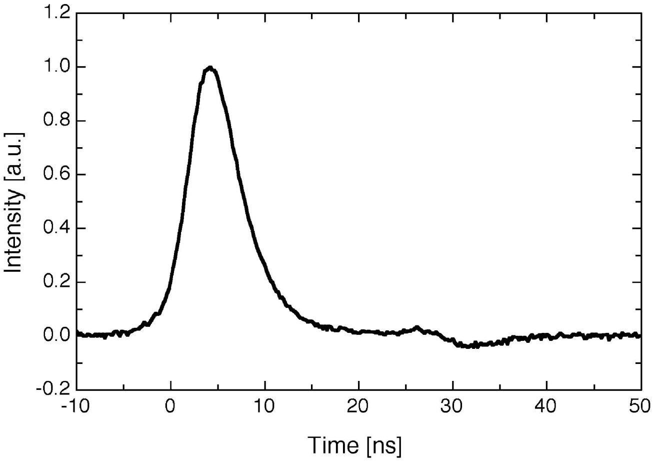

FIGURE 5 Passively Q-switched pulse recorded by a fast digital scope and a sub-nanosecond photodiode

However, the high peak power estimated for the Q-switched pulses generated by the present set-up, approximately 26 kW, seemed to be suitable for efficient second-harmonic generation as well as for other non-linear frequency conversion processes.

We performed a frequency doubling experiment with a 12-mm-long type-II KTP crystal, antireflection coated both at 532 nm and 1064 nm. The pump beam was focused in the KTP crystal to an optimum spot size of approximately 90-μm radius (at $1/e^2$ of peak intensity), as was verified experimentally. As much as 1.54 W at 532 nm (≈ 48% conversion efficiency) were generated from the 3.2-W beam at 1064 nm transmitted by the focusing optics. The beam quality corresponded to an $M^2 < 1.2$. Although the measured second-harmonic conversion is already interesting for many practical applications, according to our experience we expected a higher efficiency for a 26-kW peak-power pulse, up to approximately 60% [5]. The discrepancy can be readily explained by the slightly worse beam quality compared to that in [5], and also by the measurement of the cross polarization (*c*) contribution, that turned out to be approximately 10% of the total average power. Also, it is possible that thermal perturbations added by the strongly heated, thin Cr:YAG crystal contributed to a slight beam-quality degradation. The polarization selection performed by the wedged vanadate crystal and the tilted output coupler could be improved, for example by increasing the wedge angle of the crystal such that the overlap of the two angular detuning curves in Fig. 2 becomes negligible. Furthermore, adding a rear concave mirror should also improve the beam quality significantly, eventually allowing higher pulse brightness as well as more efficient non-linear conversion processes.

3 Conclusions

We have demonstrated a diode-pumped Nd:YVO$_4$ PQS laser with a novel polarization selection technique (patent pending), by which we operated a compact resonator in high-pulse-energy mode with ordinary wave polarization (*a*), corresponding to the smallest value of the emission cross section. This allowed us to take advantage of the highly efficient, polarized emission of vanadate lasers with a simple cavity design for effective PQS operation, avoiding risky, damage-prone intracavity tight-focusing geometries usually required by *c*-polarized vanadate lasers. High average power (3.8 W) and high pulse peak power (> 20 kW) were demonstrated, and straightforward improvements over the present set-up have been proposed. The peak power achieved with the present set-up is already approximately 18-times higher than that for a previous device we developed, based on a standard *c*-polarized Nd:YVO$_4$, diode-pumped at a slightly lower power of approximately 15 W [5].

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