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Diode pumped Nd:YVO_4 laser at 1.34 μm Q-switched and mode locked by a V^{3+}:YAG saturable absorber

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Abstract

A diode-pumped Nd:YVO_4 laser passively Q-switched and mode locked by V^{3+}:YAG generates as much as 505-mW average power at 1342 nm (30% of the cw output) in trains of sub-nanosecond pulses with energy as high as 0.7 μJ and repetition rates in the range 10–50 kHz. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

In the last few years the interest in passively Q-switched and mode-locked lasers has significantly grown. The solid-state saturable absorber crystal V^{3+}:YAG has been proved an effective material for applications in the second telecommunication window near 1.3 μm. Owing to its favourable ground- and excited-state absorption characteristics, V^{3+}:YAG allows passive Q-switching of solid-state lasers in the wavelength range 1–1.3 μm [1–3]. Additionally, its relatively fast absorption recovery time of the first excited level of few nanoseconds allows combined Q-switching and mode-locking operation when the resonator is properly designed. Nd:YVO_4 is among the most efficient laser materials suitable for diode pumping at 808 nm and with emission at 1.3 μm [4]. Passive mode locking was recently reported in a Nd:YVO_4 laser passively Q-switched at 1064 nm with Cr^{4+}:YAG [5], and was explained as the result of saturation and fast recovery time of excited-state absorption. In this communication we report on what is to our knowledge the first diode-pumped Nd:YVO_4 laser Q-switched and mode locked by V^{3+}:YAG at 1342 nm. A simple analytical model describing mode-locking and Q-switching regimes [6] have been applied to resonators including V^{3+}:YAG saturable absorber crystals and is compared with the experimental results. According to it, it has been shown experimentally that relatively long

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resonators (1–1.5 m) lead to the generation of extended, nearly fully modulated microsecond trains of sub-nanosecond pulses.

2. Experiment

A 12-W fibre coupled laser diode array emitting at 808 nm from an 800-μm fibre with numerical aperture of 0.16 was used to pump longitudinally a 5-mm long 0.5%-doped *a*-cut Nd:YVO$_4$ crystal, which was placed at one end of the resonator. The vanadate crystal was coated on one facet for high reflectivity at 1342 nm and high transmissivity at 808 nm, whereas the second facet was antireflection coated at 1342 nm. Additionally, the laser crystal was cut with 1°-wedged end facets to avoid etalon effects. As much as 9.7 W of pump power were eventually absorbed by the vanadate crystal, due to Fresnel losses in the pump optic re-imaging unit.

The Z-shaped resonator (Fig. 1) was designed for effective mode matching of the pump beam (≈400–500 μm diameter) in the laser crystal (mode radius $w_g \approx 200$–250 μm) and for adjustable focusing in the saturable absorber which was placed at the opposite end of the cavity. Several folding mirror pairs were used to investigate pulsed operation at different cavity lengths and with different focusing ratios in the saturable absorber.

The folding angles were kept as small as possible to limit astigmatism in the output beam, which was a nearly circular TEM$_{00}$ in all the conditions.

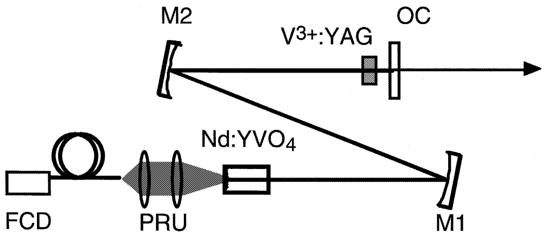

Fig. 1. Resonator layout. FCD: fibre coupled diode array; PRU: pump re-imaging unit; M1: first concave folding mirror (radius of curvature *R*1); M2: second concave folding mirror (radius of curvature R2); OC: output coupler.

The V^{3+}:YAG saturable absorber was grown at the Institute of Electronic Material Technology (Warsaw, Poland). The critical issue in V^{3+}:YAG crystal fabrication is the minimization of the ratio between non-saturable losses and saturable losses, which depends on the technology of material growth and thermo-chemical processing of V^{3+}:YAG crystals [7]. In particular, V^{3+}:YAG crystals were grown using the Czochralski method; they were subsequently exposed to thermal post-processing in reducing atmosphere to increase significantly the concentration of V^{3+} ions in tetrahedral positions of YAG crystal lattice, which have been identified as the responsible of the saturable absorption in the near infrared. V^{3+}:YAG crystals with low-signal single-pass transmission in the range 68–94% at 1342 nm were available, with antireflection coating at 1342 nm. Among them, the crystal allowing best performances in Q-switching [3] and Q-switching/mode locking was a 1-mm thick sample with 89% small-signal transmission, including some non-saturable losses (≈15% of the total) of uncertain origin related to the crystal growth process. The saturable absorber was placed near the output coupler with 10% transmission, where the mode radius was $w_a \approx 30$–150 μm, depending on the resonator configuration (see Table 1).

The laser behaviour of several resonator geometries with variable lengths in the range 0.35–1.5 m was investigated. The folding concave mirrors were chosen to trade off the cavity stability and the ratio between the mode size in the gain material and that in the saturable absorber, which is a critical parameter influencing Q-switching operation. The shortest resonators employed concave mirrors of curvature radius $R1 = 100$ mm and $R2 = 75$ mm, whereas the longest resonator used two equal folding mirrors with $R1 = R2 = 500$ mm. All these dynamically stable resonators had comparable performances in cw operation using the 10%-transmissivity output coupler, with ≈30% slope efficiency and up to ≈2.2 W output power in a nearly diffraction-limited beam. The Q-switching/mode-locking results are summarized in Table 1.

With the V^{3+}:YAG inserted in the cavity, the shortest resonator generated the highest average

Table 1
Summary of experimental results of Q-switching/mode locking

Cavity length (mm)	$R1$ (mm)/ $R2$ (mm)	w_g (μm)/ w_a (μm)	P_{cw} (mW)	$T_{repetition}$ (μs)	$E_{envelope}$ (μJ)	$T_{envelope}$ (ns)	E_{pulse} (μJ)
354	100/75	200/80	505	67	34	160	0.5
855	500/100	250/30	250	100	25	200	0.71
1465	500/500	200/150	420	20	8.4	900	0.09
1465 (KTP)	500/500	200/150	280	30	8.4	1200	0.07

output power (505 mW) and the highest energy in a 160-ns long Q-switching envelope (34 μJ). The Q-switching pulse envelope was detected by a sub-nanosecond InGaAs photodiode and displayed either on a 500-MHz digital scope or on a 500-MHz analog scope, clearly showing the generation of a single 0.5-μJ sub-nanosecond pulse with round-trip period. However, the Q-switching envelope was not fully modulated in these conditions.

Increasing the resonator length, the Q-switching envelope stretched more than linearly with respect to the round-trip time, yielding ≈1-μs long nearly fully modulated mode-locked pulse trains with the 1.5-m resonator (Fig. 2). The average power decreased slightly to 420 mW, whereas the pulse train energy was reduced to 8.4 μJ, owing to the decreased Q-switching strength: the ratio between the mode size in the gain medium and in the saturable absorber was smaller than with the shorter resonators, as shown in the third column of Table 1. The critical resonator length yielding nearly 100% modulation of the Q-switching envelope was ≈0.85 m, corresponding to a round-trip time of 5.7 ns.

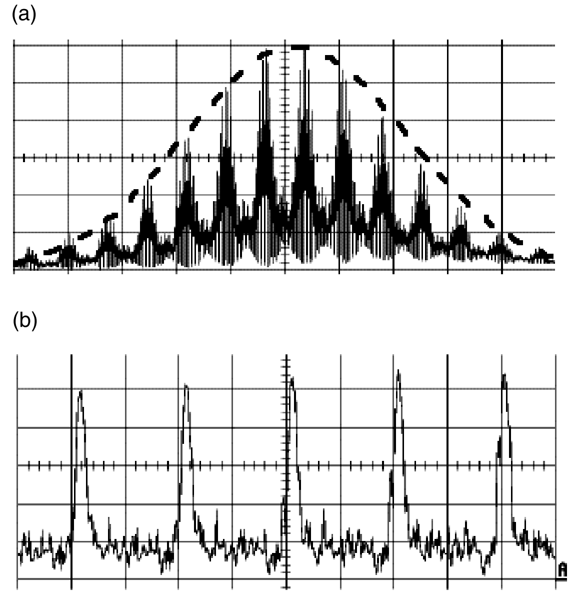

Fig. 2. (a) Q-switching mode-locking envelope (the modulation is an artefact due to the digitization process: the smooth envelope actually displayed on the analog scope is indicated by the dashed line); horizontal scale 200 ns/division. (b) Sub-nanosecond pulses with round-trip repetition time; horizontal scale 5 ns/division.

We did not attempt to measure accurately the pulse width of the mode-locking pulses, as an autocorrelator for this particular wavelength and relatively long pulse duration was not available. In any case, as our oscilloscope traces suggest, we have no reasons to believe that they could be significantly shorter than those measured in Ref. [1] using a flashlamp-pumped laser (300–500 ps).

Finally, close to the V^{3+}:YAG element we inserted a 5-mm KTP non-linear crystal cut for type II second harmonic generation at 671 nm (with dual-band antireflection coating at 1342 and 671 nm), introducing a passive negative feedback effect [8] which effectively stabilized the pulse train peak envelopes as well as the Q-switching repetition rate, reducing their fluctuations from 5% to 10% to ≈2%. The pulse width displayed by the digital scope increased by ≈20% with respect to the configuration without the KTP, as expected with the introduction of a second harmonic power limiter and the original pulse width being not much shorter than the 0.5-ns risetime of the photodetector (in agreement with earlier measurements reported in Ref. [1]). The second harmonic generation was not optimized for the highest efficiency, as this was unnecessary for the passive negative feedback and furthermore it required major changes in cavity design, hence the output power at 670 nm was only a small fraction of that in the fundamental beam.

3. Discussion

In an earlier experiment with diode-pumped neodymium lasers at 1.3 μm Q-switched by V^{3+}:YAG [3] in relatively short resonators (<10 cm, i.e. round-trip time $T_R < 0.6$ ns), we observed smooth Q-switching envelopes of 10–30 ns, with pulse energy and duration depending on the V^{3+}:YAG initial transmission. The condition that needed to be fulfilled for effective passive Q-switching is provided by Kärtner et al. [6] in the approximation of adiabatic response of the saturable absorber (see also Ref. [9]), which certainly applies to our case (pulse dynamics much slower than the absorber relaxation time $\tau_a \approx 5$ ns [10]):

$$\frac{\sigma_a}{\sigma_g}\frac{A_g}{A_a} > \frac{1}{2q_0}\frac{T_R}{\tau_a} \tag{1}$$

The left side (expressing the ratio of the effective saturation energies in the gain medium (subscript g) and in the saturable absorber (subscript a)) was usually >1 in our experimental conditions, whereas the right side was <1, hence ensuring successful passive Q-switching in nearly all the conditions investigated in Ref. [3], with saturable small-signal loss $q_0 \approx 0.1$–0.2.

Ref. [6] also provides a criterion for the onset of Q-switching/mode locking:

$$\frac{\sigma_a}{\sigma_g}\frac{A_g}{A_a} > \frac{1}{2q_0} \tag{2}$$

Note that as the round-trip time T_R exceeds the recovery time of the absorber τ_a Eq. (1) predicts a threshold for Q-switching higher than for Q-switching/mode locking, in agreement with our observations. Indeed, it was observed experimentally that the modulation depth in the Q-switching envelope did increase with the resonator length, reaching nearly full modulation as the round-trip time approached the V^{3+}:YAG recovery time.

Notwithstanding the ≈5-ns recovery time of the V^{3+}:YAG saturable absorption (which provided the main pulse shaping mechanism), mode-locking pulses significantly shorter (<1 ns) were observed (Fig. 2), in agreement with observations made in Ref. [11]. In any case we have indications that our sub-nanosecond pulses are longer than those observed by Chen et al. [5] in a vanadate laser passively modulated by Cr^{4+}:YAG, which exploited a much faster relaxation effect in the saturable absorber to produce ≈100 ps pulses at 1064 nm.

Though in our experiments the observed Q-switched/mode-locked pulses reached peak powers interesting for many non-linear optics applications, and especially interesting for the second telecommunication window near 1.3 μm, often it would be more desirable a true cw mode-locked source owing to the improved stability and shorter pulses, even at reduced peak powers. Unfortunately, it can be shown that it is not realistic to expect in practice the suppression of the Q-switching instability observed in the vanadate laser passively modulated by V^{3+}:YAG. A useful criterion was proposed by Hönninger et al. [11], as the result of a perturbative analysis based on a rate equation model, yielding the critical pulse energy required to suppress the Q-switching instability and to obtained cw mode locking:

$$E_c = \sqrt{2q_0 E_{\mathrm{sat},L} E_{\mathrm{sat},A}} \tag{3}$$

where $E_{\mathrm{sat},L}$, $E_{\mathrm{sat},A}$ are the saturation energies of the laser crystal and the V^{3+}:YAG crystal (≈170 and ≈300 nJ respectively, considering the minimum spot sizes used in the experiment). $2q_0$ is the round-trip small-signal saturable loss of the V^{3+}:YAG.

Substituting in Eq. (3) the parameters of our laser, we obtain a critical energy $E_c \approx 3$ μJ, much higher than the value of intracavity pulse energy that might correspond to a cw mode locking in our laser set-up. On the other hand, assuming an average intracavity power level ≈ 20 W as in our cw laser, the round-trip time should be >150 ns, requiring impractical long resonators (perhaps fibre lasers might successfully implement cw passive mode locking with V:YAG at 1.3 μm). These considerations hold true also assuming saturable losses $2q_0$ of only few percent, as is usually the case of SESAMs devices [12], and a mode area in the gain medium smaller by one order of magnitude. Of course this would rise concerns about laser damaging.

It is clear that the basic difference with SESAM technology is the much lower absorption cross-section of solid-state insulating saturable absorber crystals such as V^{3+}:YAG and Cr^{4+}:YAG.

Therefore, one should investigate other techniques to suppress Q-switching fluctuations, such as pulse-shortening passive negative feedback effects [13]. Intracavity second harmonic conversion is not useful in our laser set-up, as the threshold for cw mode-locking stable against Q-switching is not significantly lowered by the power-dependent loss introduced by the KTP crystal [8].

Finally, it is worth noting that the exploitation of different non-linear loss mechanisms with relaxation times much faster than that of the first excited state of the saturable absorber, i.e. up-conversion and excited-state absorption, might produce shorter mode-locking pulses.

4. Conclusions

In conclusion, we have demonstrated a novel Q-switched and mode-locked diode-pumped laser at 1342 nm, which can be useful in non-linear optics and optical testing of telecommunication devices at this wavelength.

It is interesting to note that readily available saturable-absorbers crystals such as Cr^{4+}:YAG and V^{3+}:YAG might be used as new passive mode lockers at least for the generation of sub-nanosecond pulses, and potentially for the generation of even shorter pulses in cw mode locking.

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