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Generation of nanosecond laser pulses at a 2.2-MHz repetition rate by a cw diode-pumped passively *Q*-switched $Nd^{3+}:YVO_4$ laser*

N.T. Nghia, N.V. Hao, V.A. Orlovich, N.D. Hung

Abstract. **We report a new configuration of a high-repetition rate nanosecond laser based on a semiconductor saturable absorber mirror (SESAM). The SESAM is conventional technical solution for passive mode-locking at 1064 nm and simultaneously used as a highly reflecting mirror and a saturable absorber in a high-*Q* and short cavity of a cw diode-end-pumped *a*-cut $Nd^{3+}:YVO_4$ laser. Two laser beams are coupled out from the cavity using an intracavity low-reflection thin splitter. The laser characteristics are investigated as functions of pump and resonator parameters. Using a 1.8-W cw pump laser diode at 808 nm, the passively *Q*-switched SESAM-based laser generates 22-ns pulses with an average power of 275 mW at a pulse repetition rate of 2250 kHz.**

Keywords: *laser cavity, saturable absorber, passive Q switching, Cr:YAG,* $Nd^{3+}:YVO_4$*, SESAM.*

1. Introduction

Compact, high repetition rate, nanosecond pulse laser sources offer simple solutions of a wide range of such applications as rapid range finding or remote sensing. One of the most effective techniques for generating nanosecond pulses is *Q* switching of diode-pumped solid-state lasers. Diode-pumped lasers have been actively *Q*-switched using an electro-optic modulator, or passively, using saturable absorption materials [1 – 3]. However, their parameters such as recovery time and modulation depth cannot be modulated freely, which limits their application as an absorber. Pure GaAs was first used for passive *Q* switching by Kajava and Gaeta [4] to obtain the pulse duration as short as 3 ns. In 2001, a *Q*-switched, self-mode-locked $Nd^{3+}:YVO_4$ laser with a $LiF:F_2^-$ saturable absorber was demonstrated by Chen et al. [5]. The *Q*-switched laser pulse has a repetition rate of 260 kHz and pulse duration of approximately 250 ns. In 2004, the characteristics of a passively *Q*-switched $Nd^{3+}:YVO_4$ laser with a $LiF:F_2^-$ saturable absorber were investigated by Villafana et al. [6]. In 2005, Pan et al. [7] used frequency selection to remove the minor pulses inside the *Q*-switching envelope and obtained pure *Q* switching with a duration of 150 ns and a repetition rate of 76.3 kHz.

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Recently, a composite semiconductor absorber fabricated specifically by the metal-organic chemical-vapour deposition (MOCVD) technique, was used both as passive *Q* switching and a coupler. In this case, the laser produced 8.3-ns pulses at a repetition rate as high as 2 MHz [8].

In present experiment, as a gain medium we used an *a*-cut $Nd^{3+}:YVO_4$ crystal whose popularity is caused by its high gain, low lasing threshold, and high absorption coefficients at pump wavelengths. This crystal has the stimulated emission cross sections at 1064 nm (25×10^{-19} cm^2), which is approximately four times higher than that of $Nd^{3+}:YAG$ (6×10^{-19} cm^2) and, in particular, its optical-to-optical efficiency under diode pumping may be larger than 60 % [5 – 10]. These advantages make the $Nd^{3+}:YVO_4$ crystal a better candidate than $Nd^{3+}:YAG$ in many applications. In recent years, $Nd^{3+}:YVO_4$ crystals have been widely used as gain media in diode-pumped all-solid-state lasers.

In this paper, we propose a novel, compact and simple resonator configuration of diode-pumped passively *Q*-switched $Nd^{3+}:YVO_4$ lasers with a semiconductor saturable absorber mirror (SESAM) to generate stable nanosecond laser pulses with a large repetition rate and high conversion efficiency. The InGaAs SESAM that is conventionally commercialised for passive mode-locking at 1064 nm is simultaneously used as a highly reflective mirror and a saturable absorber in a high-*Q* and short cavity of a cw diode-end-pumped passively *Q*-switched $Nd^{3+}:YVO_4$ laser. Two laser beams are simultaneously coupled out using an intracavity low-reflection thin splitter. The laser characteristics are investigated as functions of pump and resonator parameters. This passively *Q*-switched $Nd^{3+}:YVO_4$ laser generates 22-ns single laser pulses with a total average power of 275 mW at a repetition rate of 2250 kHz.

To the best of our knowledge, this pulse repetition rate is the highest one ever generated directly from a diode-pumped passively *Q*-switched $Nd^{3+}:YVO_4$ laser with a conventional SESAM. To make a comparative analysis, we used a $Cr^{4+}:YAG$ crystal (initial transmission of 90 %) as an intracavity saturable absorber for passive *Q* switching of the $Nd^{3+}:YVO_4$ laser. Comparisons between these passively *Q*-switched lasers show the advantages of using the SESAM in order to produce stable passively *Q*-switched lasing with a high pulse repetition rate and high conversion efficiency.

2. Experimental

Figure 1 presents the scheme of our passively *Q*-switched diode-pumped $Nd^{3+}:YVO_4$ laser. The gain medium of size 3×3×3 mm made of a 0.1 % doped $Nd^{3+}:YVO_4$ crystal (Casix) is pumped at 808 nm by a 2.0-W cw laser diode (ATC-Semiconductor Devices). By using the laser diode with a 200-μm

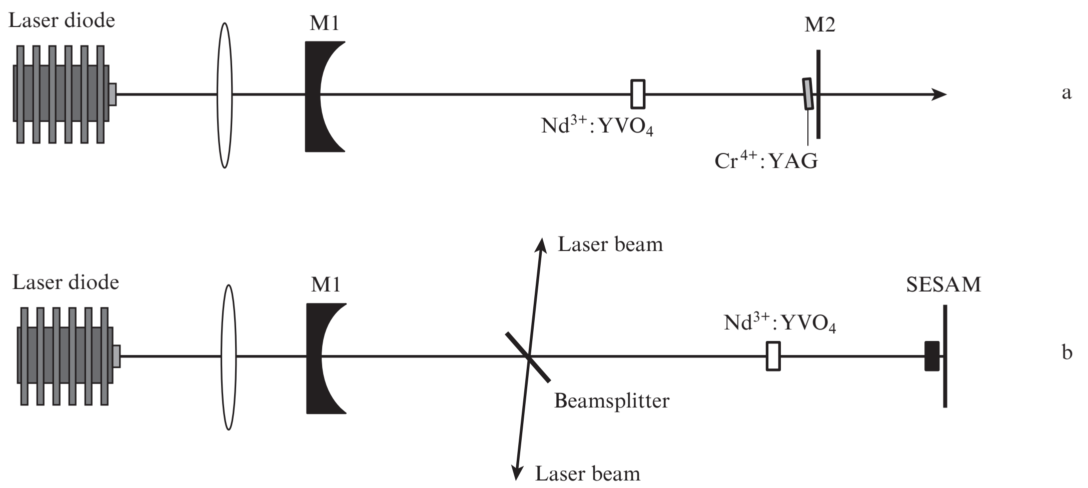

Figure 1. Scheme of the diode-pumped Nd^{3+}:YVO_4 laser passively Q-switched by (a) Cr^{4+}:YAG and (b) SESAM; M1 and M2 are the resonator mirrors.

stripe size and a simple optical coupling system consisting of a single lens with a 2.5-cm focal length, we were able to achieve a small pump spot in the Nd^{3+}:YVO_4 crystal while maintaining a compact setup.

For the sake of a comparative analysis of passively Q-switched lasers with a SESAM and a Cr^{4+}:YAG crystal, firstly we used as a saturable absorber a 1-mm-thick Cr^{4+}:YAG crystal (Casix) with a 90% initial transmission. The laser resonator based on the a-cut Nd^{3+}:YVO_4 laser passively Q-switched by the Cr^{4+}:YAG crystal is a stable linear resonator (Fig. 1a). In our experiment, using a 1.8-MW cw pump laser diode at 808 nm, the Nd^{3+}:YVO_4 laser passively Q-switched by the Cr^{4+}:YAG crystal generated the 35-ns pulses at the maximum repetition rate of 42 kHz and the slope efficiency of 10.5%.

For a given Nd^{3+}:YVO_4 laser, in order to obtain theoretically larger pulse repetition rates, a larger diode pump power and shorter resonator length are required. The latter is feasible using the advantages of the SESAM that can be simultaneously employed as a highly reflecting mirror and a saturable absorber for passive Q switching. Figure 1b shows the configuration of the a-cut Nd^{3+}:YVO_4 laser passively Q-switched using the SESAM. We used the SESAM (SE-1064-2-0) provided by BATOP [9] as a rear highly reflecting mirror and an intracavity saturable absorber. The parameters of the SESAM (Batop) are presented below.

Laser wavelength λ/nm	1064
High reflection range ($R > 99\%$)/nm	1020–1110
Absorbance A_0 (%)	2
Modulation depth ΔR (%)	1.2
Saturation fluence F_{sat}/μJ cm^{-2}	70
Relaxation time τ/ps	20
Nonsaturable loss A_{ns} (%)	less than 0.8
Damage threshold/MW cm^{-2}	800
SESAM surface area/mm	5×5
SESAM thickness/μm	350
Protective coating	dielectric front layer

The wavelength dependences of the SESAM reflectivity are presented in Fig. 2. The short (3 cm) high-Q resonator of the Nd^{3+}:YVO_4 laser is formed by the SESAM [used simultaneously as a highly reflecting mirror (M2) and an intracavity saturable absorber] and a rear mirror (M1) of curvature radius of 5 cm (highly reflecting at 1064 nm and weakly reflecting at 808 nm). The laser radiation is coupled out by using an intracavity low-reflection thin splitter (4%) placed at a Brewster angle with respect to the polarisation and wavelength in order to decrease the pump beam losses (Fig. 1b). To alleviate the thermal load, the Nd^{3+}:YVO_4 laser crystal and the SESAM were attached to copper blocks. Detailed information about the laser design is presented in papers [10, 11].

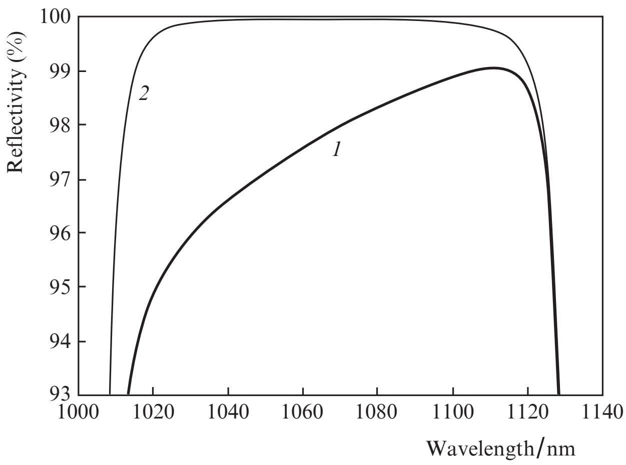

Figure 2. Reflectivity of the SESAM (SE-1064-2-0) in the unsaturated (*1*) and saturated (*2*) states.

The output pulses of the Q-switched lasers were monitored by a fast photodiode (Hamamatsu, 0.3-ns rise time) and a digital oscilloscope (1.5 GHz, sample rate of 20 GHz, Tektronix TDS 7154 B). Pulse energies were measured with broadband power energy meters (Laser Precision and Melles Griot).

Figures 3 and 4 present the characteristics of the Nd^{3+}:YVO_4 laser passively Q-switched by the SESAM. Using the 1.8-W pump laser diode at 808 nm, the SESAM-based Q-switched laser produced the 22-ns pulses at a pulse repetition rate as high as 2.15 MHz and an average power of 275 mW, corresponding to the conversion efficiency of 15.3% (Fig. 3). Using a 2.0-W maximal power of the pump laser diode, the laser produced the Q-switched pulse of nearly the same duration

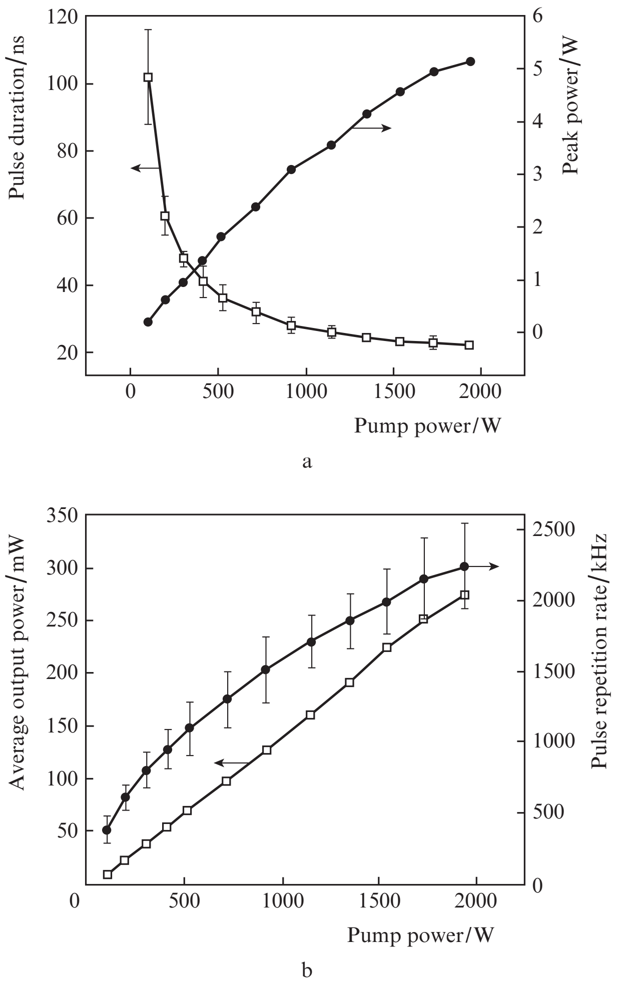

Figure 3. Characteristics of a Nd^{3+}:YVO_4 laser passively *Q*-switched by the SESAM: (a) pulse duration and peak power, (b) average output power and pulse repetition rate.

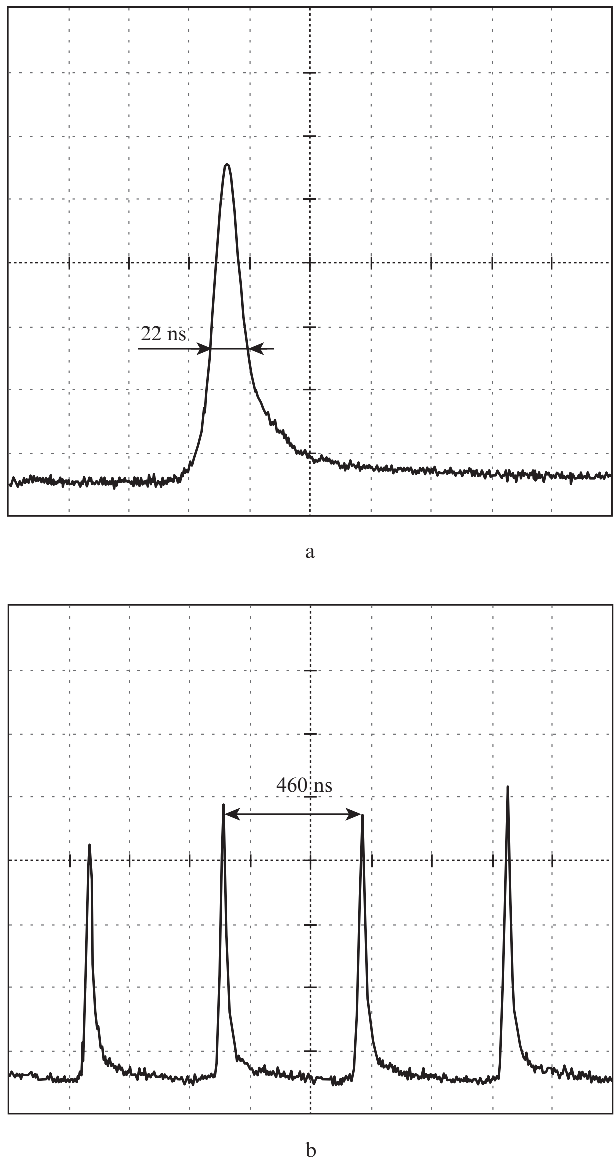

Figure 4. Oscillograms of a laser pulse (a) and a train of pulses (b) from the Nd^{3+}:YVO_4 laser passively *Q*-switched by the SESAM.

(22 ns) but at a higher pulse repetition rate of 2.25 MHz. However, the pump laser diode power of 1.8 W is routinely used in our laser experiments.

Evidently, the SESAM-based *Q*-switched laser simultaneously provided a shorter *Q*-switched pulse duration, better laser efficiency and, in particular, a considerably higher pulse repetition rate (as high as 2.25 MHz) than those of the Cr^{4+}:YAG *Q*-switched laser.

The nanosecond laser pulses at 1064 nm from the two outputs of the SESAM-based *Q*-switched Nd^{3+}:YVO_4 laser were measured to be identical. The nanosecond laser resonator configuration with such two outputs is quite attractive for the applications where a high pulse repetition rate equal to a multiple of that obtained by synchronisation electronics is demanded or where the temporal interval between two laser pulses is to be controlled.

Furthermore, the configuration of the *a*-cut Nd^{3+}:YVO_4 laser passively *Q*-switched by the SESAM demonstrated the advantages of a SESAM for passive *Q* switching of solid-state lasers. First, the resonator length can be maintained as short as possible and, therefore, shorter *Q*-switched pulse widths are obtainable. Secondly, no specific requirements to the SESAM fabrication are needed and use can be made of only conventional SESAMs, the band gap of the SESAM being controlled and adapted to other laser materials at different wavelengths. Finally, this resonator configuration offers enough design freedom to permit independent adjustment of the saturation intensity.

3. Conclusions

A simple and compact laser resonator configuration of cw diode-end-pumped high repetition rate Nd^{3+}:YVO_4 lasers passively *Q*-switched by a conventional SESAM (for mode-locking) has been demonstrated. Using a 2.0-W cw pump diode power, this laser provides the 22-ns pulse with a laser conversion efficiency larger than 15.0% and a pulse repetition rate as high as 2250 kHz. The pump and laser resonator parameters can be improved to get a higher pulse repetition rate and shorter pulse width as well as used with other laser materials at different wavelengths.

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References

1. Feldman R., Shimony Y., Burshtein Z. *Opt. Mater*., **24**, 393 (2003).
2. Miller I., Alcock A., Bernard J., in *Advanced Solid State Lasers* (Washington, DC, OSA, 1992) Vol. 13, p. 332.
3. Spühler G.J., Paschotta R., Fluck R., Braun B., Moser M., Zhang G., Gini E., Keller U. *J. Opt. Soc. Am. B*, **16**, 367 (1999).
4. Kajava T.T., Gaeta A.L. *Opt. Lett*., **21**, 1224 (1996); *Opt. Commun*., **137**, 93 (1997).
5. Chen Y.F., Tsai S.W., Wang S.C., Chen J. *Appl. Phys. B*, **73**, 115 (2001).
6. Villafana E., Alexander R., Kir'yanov V. *Opt. Commun*., **242**, 241 (2004).
7. Pan H.F., Xu S.X., Zeng H.P. *Opt. Express*, **13**, 2755 (2005).
8. Wang Y.G., Ma X.Y., Peng J.Y., Tan H.-M., Qian L.-S. *Appl. Opt*., **45** (25), 6616 (2006).
9. http://www.batop.com/sesam/.
10. Nghia N.T., Khanh D.Q., et al. *Comm. Phys. (VAST)*, **19**, Special issue, 145 (2009).
11. Nghia N.T., Hoang N.D., Thang D.D., et al. *Proc. 5th Asian Symposium on Intense Laser Science* (Beijing, China, 2010) pp 354–358.