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# Stable mode-locked operation of a low repetition rate diode-pumped Nd:GdVO<sub>4</sub> laser by combining quadratic polarisation switching and a semiconductor saturable absorber mirror

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**Abstract:** In this paper, we present the mode-locked operation of an ultra-robustly stabilised Nd:GdVO<sub>4</sub> laser with low repetition rate by combining quadratic polarisation switching and a semiconductor saturable absorber mirror (SESAM). In addition, similar experiment was also done with Nd:YVO<sub>4</sub>. For Nd:GdVO<sub>4</sub>, 16-ps pulses at 1063nm with a repetition rate of 3.95MHz have been obtained for a laser average output power of 1.4W. For Nd:YVO<sub>4</sub>, the performance was 2.5W of average power for 15-ps pulses at 1064nm. Moreover, we demonstrate experimentally the advantage of combining these two passive mode locking techniques in terms of stability ranges. We show how the dual mode-locking technique is crucial to obtain a stable and long-term mode-locked regime in our case of a diode-pumped Nd:GdVO<sub>4</sub> laser operating at low repetition rate and more generally how this dual mode-locking technique improves the stability range of the mode-locked operation giving more flexibility on different parameters.

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OCIS codes: (140.3580) Lasers, solid-state; (140.4050) Mode-locked lasers.

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## 1. Introduction

Nowadays, mode-locked (ML) picosecond lasers, producing large peak power are key instruments for a lot of biological applications such as in fluorescence measurements, ultra-fast spectroscopy and microscopy [1]. Furthermore these lasers have been demonstrated to be also suitable for micromachining, in particular for the treatment of temperature-sensitive materials with an ablation process based on multi-photon-ionisation [2]. For this last application it seems very interesting to develop a very robust, highly-efficient system based on diode-pumped solid-state lasers (DPSSL). And, for picosecond DPSSLs, Neodymium-doped crystals (in particular Nd-doped vanadates) are particularly suitable because of their high gain [3]. In this point of view, the Neodymium-doped Gadolinium Orthovanadate crystal (Nd:GdVO<sub>4</sub>) seems to appear an interesting alternative to the well-established Neodymium-doped Yttrium Orthovanadate crystal (Nd:YVO<sub>4</sub>) [3,4,5]. Even though they have a reduced emission cross section, it was already demonstrated that Nd:GdVO<sub>4</sub> crystals have similar performances in terms of power compared to Nd:YVO<sub>4</sub> crystals. Nevertheless, it has extra advantages such as a broader absorption bandwidth at 808nm (which allows the pumping by high-power laser diodes as also possible with Nd:YVO<sub>4</sub>), a higher thermal conductivity and a higher damage limit value [3,6,7]. Due to these properties it has been interesting to explore the performances of such crystals for the development of high power Nd:GdVO<sub>4</sub> picosecond lasers operating at a low repetition rate.

In fact, mode-locked operation with Nd:GdVO<sub>4</sub> in the range of some hundreds of MHz has already been achieved [8,9]. We are demonstrating in this paper the first (to our best knowledge) very low repetition rate mode-locked operation with a Nd:GdVO<sub>4</sub> crystal. As we will see, this realisation is more difficult than with Nd:YVO<sub>4</sub>. That is the reason why we developed a dual ML technique in order to achieve ultra-stable ML regime. The principle consists in combining two different techniques of mode-locking, on the one hand a Semiconductor Saturable Absorber Mirror (SESAM) [10] and on the other hand the quadratic polarisation switching (QPS) using a nonlinear crystal [11,12,13]. We will see that this technique allows us to demonstrate a very stable and robust low repetition rate system.

## 2. The dual ML technique: quadratic polarisation switching and SESAM

The quadratic polarisation switching (QPS) is a mode-locking technique based on the non-linear polarisation rotation in a type II nonlinear crystal (NLC). In such a NLC the wave of least initial amplitude gets completely decreased if the NLC is well orientated for second harmonic generation (SHG) and if the incoming wave is fragmented in two orthogonal components. In this case and after a round trip in the NLC, the orientation of the intracavity linear polarisation beam depends on the intensity. By introducing a polariser between the amplifying medium and the NLC, a device with an intensity dependent transmission can be realised as demonstrated by V. Couderc et al. [11-13]. Just by changing the orientation of the NLC versus the intracavity polarisation this technique is adjustable for any range of output power which is increasing the versatility of a laser cavity. Thus we demonstrated a stable ML

Nd:YVO<sub>4</sub> laser with an output power of 2W at 4MHz repetition rate by using QPS technique. Nevertheless, this mode-locked source required tricky polarisation realignment at the starting of the laser which means that the tolerance of the axial rotation of the half-wavelength plate was in the range of less than 1° and had to be adjusted very accurately. Furthermore we observed experimentally that this technique is not applicable straightforwardly to Nd:GdVO<sub>4</sub>. After every polarisation and crystal-orientation realignment we achieved ML for only a few seconds. This short time ML operation could be explained by a very limited parameter range for stable ML operation. In fact, when alignment allows ML, small slow varying perturbations (such as variations of thermal loads between ML and Q-switching) could disrupt the laser performance and then stop the ML.

In order to take advantage of QPS, we tried the dual ML technique adding a SESAM. To obtain the effect of passive mode-locking, i.e. ps pulse generation, the SESAM can be used in a wide range of laser cavities by replacing the total reflector mirror of the cavity by such a saturable absorber. In this vein, mode-locked pulses of 10's of picoseconds and even femtoseconds can be produced. One of the main advantages of a SESAM is the self-starting of the mode-locked operation. Nowadays, the absorption wavelength, the saturation energy and the recovery time of SESAMs are well-definable parameters [10] and these components are reliable and easy to use. However, SESAMs are sensitive to burning damage. In fact it is well known that some parameters (focus spot on SESAM [10], intracavity power, etc) are very critical and damage problems can be observed when these parameters are not correctly adjusted or when perturbations occur. This is particularly crucial in the case of very low repetition rate ML. Our aim was then to use a SESAM in a relatively low risk setup configuration, using a dual mode-locking technique (here QPS) to extend the critical parameters of the cavity. But, in order to be sure that the increase of the stable ML range was not only due to the SESAM (independently of the QPS) we tried the mode-locking of our cavity with SESAM alone. The ML stability was only for short term, in the range of ten's of seconds. This experiment was tried with different SESAMs with saturable absorptions from 1 to 4% and no significant stability change was observed in our experiment.

Our experimental conclusion is that the quadratic polarisation switching works relatively well with Nd:YVO<sub>4</sub> but not in the case of Nd:GdVO<sub>4</sub>. To overcome this problem, we explored the alternative way by combining both techniques, QPS and SESAM. In fact, low repetition rate ML with Nd:GdVO<sub>4</sub> lasers is more difficult to obtain than with Nd:YVO<sub>4</sub>. This could be explained by the fact that Nd:GdVO<sub>4</sub> has a lower emission cross section (subsequently a lower gain) than Nd:YVO<sub>4</sub> [3]. We will see how the use of this dual ML technique allowed obtaining stable ML for Nd:GdVO<sub>4</sub>. We also applied it to Nd:YVO<sub>4</sub> to see whether it also improves the overall stability of the laser.

### 3. Experimental setup

The performed experiment is a diode pumped solid state laser using a 10-mm long, 0.1%-doped Nd:GdVO<sub>4</sub> crystal (a-cut, from Castech) and accordingly a 10-mm long, 0.1%-doped Nd:YVO<sub>4</sub> crystal (a-cut, from Castech) as the amplifying medium. To pump these crystals, we used a laser diode at 808 nm (from LIMO, HLU30F400-808) with a maximum output power of 30W corresponding to 27W incident power on the crystals. The laser cavity length is increased with a multiple pass cavity (MPC) [14]. In order to obtain a low repetition rate, we realised a cavity length of 38 m corresponding to a repetition rate of nearly 4 MHz. As shown in fig. 1, the end mirror of the MPC has been replaced by a SESAM (BATOP 234-II-3;  $\lambda=1064$  nm; saturable absorption = 1.8 %). Thanks to the dual-ML technique, the focus spot is not so critical and no concave mirror has been used to focus the laser on the SESAM. The focus spot on the SESAM is then in the millimetre range in diameter (waist of 0.73 mm according to ABCD-matrix simulation) and the SESAM is operating in a safe condition of power density. At the other end of the cavity we used a plane output coupler mirror (T=27 % at 1064 nm) combined with a type II Potassium Titanyl Phosphate (KTP) crystal with a length of 8 mm to perform the quadratic polarisation switching (QPS). Between the actual amplifying crystal and the KTP crystal a polariser and a half-wavelength plate have been

placed for the purpose of obtaining QPS by setting up the saturable reflection of this non-linear mirror. The QPS is optimised for the half-wave plate angle of  $5^\circ$  from one of the neutral axis of the non-linear crystal (corresponding to an angle  $\Theta$  of  $10^\circ$  for the incident laser polarisation). The typical order of nonlinear transmission is (for small  $\Theta$ )  $\Delta t \approx 1 - \cos\Theta$  leading in our case to 1.5 %. One can notice the large difference to the Stankov ML technique [15] where the optimum polarisation orientation is close to one given the maximum SHG efficiency. One of the advantages of the QPS over the Stankov ML technique is then to operate close to the SHG extinction which thus limited the power lost in the green beam. Moreover no critical phase condition is required between the fundamental and the second harmonic waves which leads to easier adjustment of the nonlinear mirror.

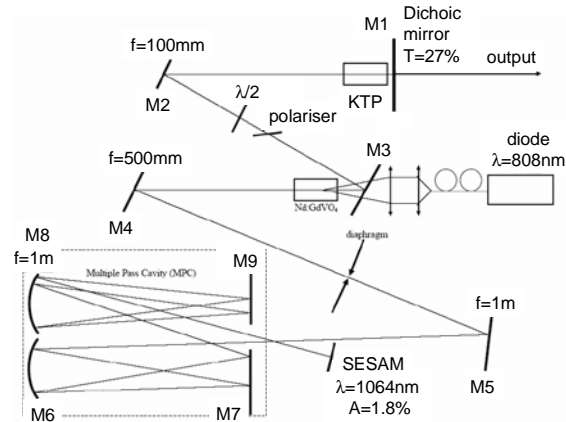


Fig. 1. Experimental setup of the laser cavity; the distances are: M1-M2: 60mm, M2-lasing crystal: 290mm, lasing crystal-M4: 300mm, M4-M6: 2310mm, M6 and M8-M7 and M9: 1050mm, M8-SESAM: 1190mm

#### 4. Results

By applying the combination of a SESAM and the QPS mode-locking technique we observed a stable mode-locked operation with a repetition rate of 3.95 MHz and an average output power of 1.4 W corresponding to an energy per pulse of 350 nJ for the Nd:GdVO<sub>4</sub> laser. For comparison, with the Nd:YVO<sub>4</sub> laser, we observed an average output power of 2.5 W (for the same repetition rate) corresponding to an energy per pulse of 638 nJ.

With an homemade long-arm autocorrelator, we measured a pulse duration of 16.5 ps for the Nd:GdVO<sub>4</sub> laser assuming an ideal sech<sup>2</sup> temporal pulse shape. Figure 2 shows the corresponding intensity autocorrelation trace. For comparison, a similar pulse duration of 14.8 ps has been obtained with the Nd:YVO<sub>4</sub> laser (also assuming an ideal sech<sup>2</sup> temporal pulse shape).

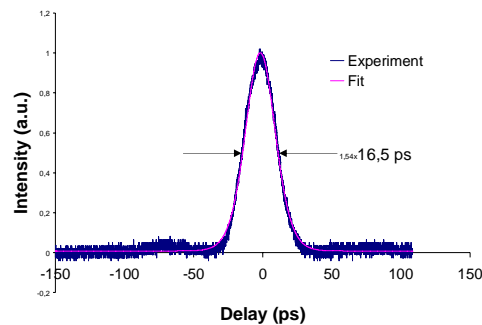


Fig. 2. Autocorrelation trace of 16.5ps pulses for the Nd:GdVO<sub>4</sub> laser using the dual ML technique

In order to demonstrate the stability of the laser we measured the pulse train with a photodiode every 30 minutes over a period of few hours. Figure 3 shows one pulse of each pulse train put on the same graph for comparison.

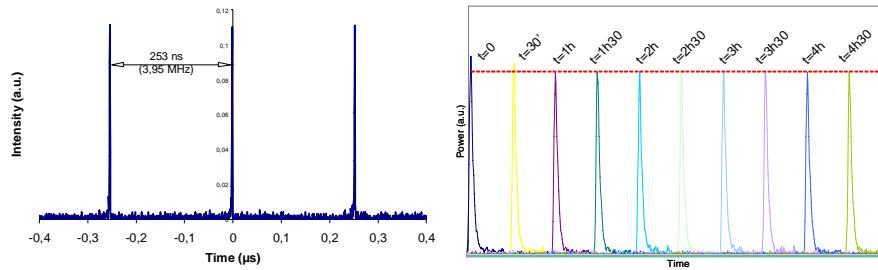


Fig. 3. Left : Pulse train. Right : Comparison of pulses taken every 30 minutes demonstrating the stable long-term mode-locked operation

In addition, we measured the spectrum (Fig. 4) using an optical spectrum analyser with a resolution of 0.07 nm. The central wavelength is 1063 nm with a bandwidth of 0.132 nm which leads to a time bandwidth product of 0.57 for Nd:GdVO<sub>4</sub>. For Nd:YVO<sub>4</sub>, the central wave-length is 1064.2 nm with a bandwidth of 0.14 nm which leads to a time bandwidth product of 0.56.

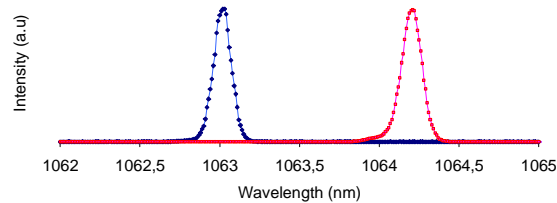


Fig. 4. Spectrum of the generated laser pulses (nm) vs. intensity (a.u.), Nd:GdVO<sub>4</sub> (blue trace at 1063.0 nm) and Nd:YVO<sub>4</sub> (red trace at 1064.2 nm)

The dual mode-locking technique combining SESAM and QPS appeared to be very interesting in terms of reliability, low-sensitivity, robustness and high stability of the mode-locked regime. Firstly, we experimentally observed that for a very long cavity using Nd:GdVO<sub>4</sub> the use of only one of these techniques leads to bad stability mode-locked operation in terms of long-term range (i.e. under the minute range). On the contrary, a significant increase of then long-term stability is obtained by applying this dual-technique. Moreover, we observed also a robustness of the system for weeks: the laser did not require any realignment when switched on. Secondly, the dual-mode-locking technique allows reducing the risk of damage of the SESAM. Actually, one could use a high-transmission output coupler both with a large spot on the SESAM which limits the peak power on the SESAM and without altering the stability of the mode-locking.

To quantify the stability, we first measured the range on which a long-term-stable mode-locked operation versus the pump power can be observed. The result of the combination of SESAM and QPS allowed mode-locked operation of the Nd:GdVO<sub>4</sub> laser ranging from 19 W to 26,1 W of pump power although the average output power is increased by a factor of two. With only a SESAM or a QPS for mode locking and without changing any parameters in the cavity, such a broad range of output power was not possible to be achieved. Out of this range, Q-switching or short term ML were observed for the Nd:GdVO<sub>4</sub>.

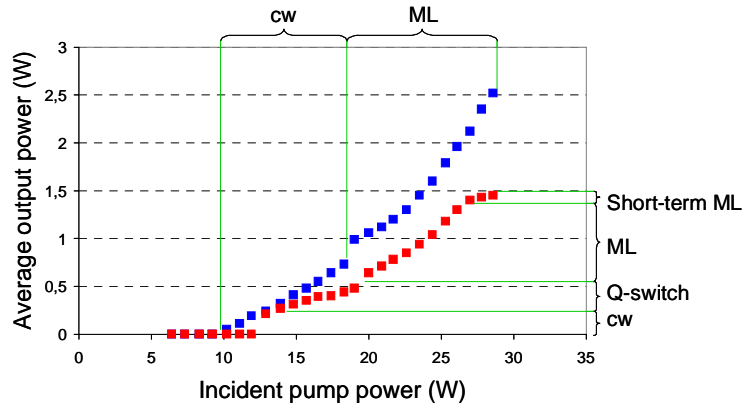


Fig. 5. Ranges of the different lasing operations for Nd:GdVO<sub>4</sub> (red curve) and Nd:YVO<sub>4</sub> (blue curve), output power (W) versus diode pump power (W)

Moreover, we also quantified the increase of the stability by measuring the half-wave plate tolerance. This parameter is interesting because we experimentally observed (with Nd:GdVO<sub>4</sub> and with Nd:YVO<sub>4</sub>) for pure QPS mode-locking and for very long-cavities that it was a very critical parameter to adjust ( $\sim 1^\circ$  of tolerance for Nd:YVO<sub>4</sub>). In the case of dual mode-locking technique, stable picosecond emission was observed for a rotation of the half wave plate between  $3^\circ$  and  $17^\circ$ . The average output power stayed almost constant (1.5 %) in this range of rotation. Afterwards, the mode-locked operation collapsed in a few seconds. Hence we demonstrated that the combination of both mode-locking techniques enlarges the stable and robust long-term mode-locked operation of a Nd:GdVO<sub>4</sub> laser.

## 5. Conclusion

We demonstrated the first low repetition rate picosecond mode-locked Nd:GdVO<sub>4</sub> laser. The combination of both a semiconductor saturable absorber mirror and the quadratic polarisation switching technique was demonstrated to be crucial in our case to obtain a self-starting, stable and long-term mode-locked operation with Nd:GdVO<sub>4</sub>. The stability was very strong for hours and did not require any alignment for starting. Moreover, relaxing the tolerance of the pulse fluence on the SESAM, the dual technique seems to be very suitable to reduce the risk of damage of the SESAM. In fact, it allows mode-locked operation with a focused spot on the SESAM excluding any damaging of it. This technique also improves the ML range compared to already published simple-ML-technique Nd:YVO<sub>4</sub> lasers. It seems then to be of very strong interest to robust industrial applications such as micro-machining. Moreover, such a robust low repetition rate picosecond laser system could be also applied typically for biological applications, especially for fluorescence lifetime measurements. Because the fluorescence lifetime of certain molecules is in the range of ten's of nanoseconds, short pulses of several tenths of picoseconds with a repetition rate of around 4 MHz are well adapted for such applications [14].

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