



HAL
open science

Passively mode-locked diode-pumped Nd:YVO₄ oscillator operating at ultra-low repetition rate

Dimitris N. Papadopoulos, Sébastien Forget, Martin Delaigue, Frédéric Druon, François Balembois, Patrick Georges

► **To cite this version:**

Dimitris N. Papadopoulos, Sébastien Forget, Martin Delaigue, Frédéric Druon, François Balembois, et al.. Passively mode-locked diode-pumped Nd:YVO₄ oscillator operating at ultra-low repetition rate. *Optics Letters*, 2003, 28 (19), pp.1838-1840. hal-00686988

HAL Id: hal-00686988

<https://iogs.hal.science/hal-00686988v1>

Submitted on 11 Apr 2012

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

when the number of passes through the MPC was arbitrarily increased, if the design starts with a small cavity (without the MPC) providing a fairly collimated beam. The main advantage of this MPC configuration is that simply changing the alignment of the plane or the concave mirrors allows almost continual control of the number of passes through the MPC. The remarkable freedom of the easy control of the beam path in the MPC is the result of the use of the two plane mirrors. Each reflection on them, when the proper alignment is achieved, actually resets the beam into the MPC in such a way that it is forced to stay in the MPC for an arbitrarily large number of round trips. It is possible that the use of three or even four plane mirrors instead of two could supply better and easier control of the number of reflections, complicating of course the final setup. Additionally, in our case it was not necessary to drill or cut the concave mirrors for the entrance and exit of the beam.³

In this system a 5-mm-long, 0.1%-doped Nd:YVO₄ crystal is pumped by a fiber-coupled laser diode at 808 nm of 15-W maximum power. Passive mode locking is achieved with the use of a semiconductor saturable-absorber mirror^{4,5} (SESAM) with a 6.1% modulation depth. During the alignment of the MPC inside the laser cavity, various repeated beam spot numbers and patterns were observed, resulting each time in the operation of the system on a number of different frequencies. Specifically, we achieved stable operation at 20, 12, 5, 3, 2.3, and 1.2 MHz by simply adjusting the alignment of the MPC. For the case of 1.2 MHz an asymmetric repeated elliptical beam spot pattern on the two concave mirrors (Fig. 2) and a corresponding pattern on the two plane mirrors provided a cavity length of approximately 121 m after 56 round trips inside the MPC. Stable, single-mode operation at a repetition rate as low as 1.2 MHz with a pulse duration of 16.3 ps and average power of 470 mW, corresponding to 392-nJ pulse energy and 24-kW peak power, is reported. The beam quality is close to the diffraction limit, with M^2 slightly greater than 1.1. Figure 3 shows a photograph of the pulse train measured with the help of a fast photodiode. Small peaks appearing just after the pulses correspond to relaxation peaks of the photodiode. Figure 4 shows the autocorrelation trace of the pulses and the respective Gaussian fit curve. The FWHM of the Gaussian curve is 23 ps, corresponding to a 16.3-ps pulse duration. The stability of the system for continuous operation during a period of several weeks was satisfactory.

The output power was seriously confined by diffraction losses at the edges of the MPC mirrors. When the SESAM was replaced with a second output mirror of the same transmission as the first one and by comparison of the power of the two outputs, the overall losses in the MPC (including the diffraction losses) were measured to be 30%. At higher frequencies, i.e., when fewer passes through the MPC and simpler beam spot patterns on the mirrors were chosen, higher output powers of several watts were possible (2.5 W for $f = 2.3$ MHz). On the other hand, operation lower than 1 MHz was also observed at 884 and 650 kHz.

However, in those frequencies severe multiple pulsing instabilities did not allow long-term operation. Nevertheless, we strongly believe that reduction of the frequencies far lower than 1 MHz is manageable with the use of this MPC configuration, if the cavity is designed from the beginning for such a purpose.

At such low frequencies and high intracavity energies and peak powers careful design is crucial to avoid malfunction of the SESAM. The value of the modulation depth of the SESAM, ΔR , the tendency for Q -switching mode locking (QML) and multiple pulsing instabilities that the SESAM introduces, and of course its damage threshold are the key points to consider in the correct design of the cavity. Generally, in

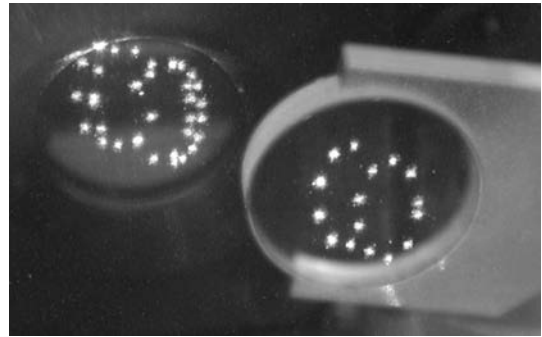


Fig. 2. Photograph of the MPC concave mirrors with the beam spot pattern on them for the 1.2-MHz repetition-rate mode-locked Nd:YVO₄ laser.

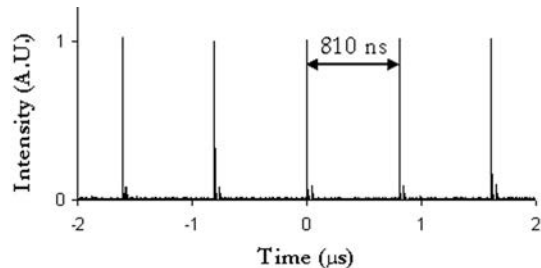


Fig. 3. Oscilloscope trace of a fast photodiode, showing the mode-locked laser pulse train of 1.2 MHz of 810-ns separation.

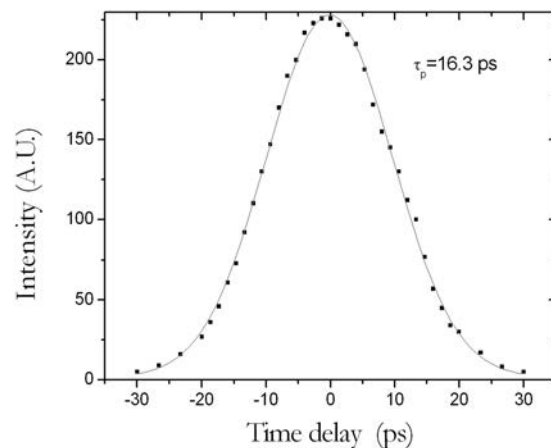


Fig. 4. Intensity autocorrelation trace showing a pulse duration of 16.3 ps assuming a Gaussian intensity profile.

passively mode-locked solid-state lasers with weak gain saturation, such as a Nd:YVO₄ laser, an initial fluctuation of the intracavity power into the cw regime monotonically increases until steady-state mode locking is reached if and only if⁶

$$\kappa P \ln(m_i) > T_r/T_c, \quad (1)$$

where m_i represents the number of the initially oscillating modes, P can be approximated by the steady-state intracavity power, T_r is the round-trip time, T_c is the effective correlation time defined by the inverse 3-dB full width $\Delta\nu_{3\text{dB}}$ of the first beat note of the free-running laser, and κ is a characteristic of the nonlinear device (SESAM) that gives the change in round-trip power gain per unit intracavity power.⁶ Because the values of P , m_i , and T_c should be considered fixed for a specific system, for very long cavities, i.e., large T_r values, the previous condition becomes demanding. Since the left-hand factor in condition (1) approximates the effective modulation depth, ΔR ,⁶ of the SESAM, choosing a sufficiently large value for ΔR is crucial. For $T_r \approx 1 \mu\text{s}$ and typical values of $\Delta\nu_{3\text{dB}}$ of approximately 1–10 KHz,⁶ a secure choice of ΔR is greater than 3%. Our system employs a SESAM with $\Delta R = 6.1\%$. On the other hand, a SESAM introduces a Q -switching tendency that can drive the laser into the unwanted QML regime. To obtain cw mode locking free of QML instabilities, one should ensure that the intracavity pulse energy E_p satisfies the condition

$$E_p > (F_{\text{sat},L} A_{\text{eff},L} F_{\text{sat},A} A_{\text{eff},A} \Delta R)^{1/2}, \quad (2)$$

where $F_{\text{sat},L}$ and $F_{\text{sat},A}$ are the saturation fluence of the gain medium and of the SESAM, respectively, and $A_{\text{eff},L}$ and $A_{\text{eff},A}$ are the effective laser mode in the gain medium and on the SESAM, respectively. Thus for a choice of large ΔR and for the fixed values of $F_{\text{sat},L}$ and $F_{\text{sat},A}$ the design of the cavity should provide values of $A_{\text{eff},L}$ and $A_{\text{eff},A}$ small enough and enough E_p that condition (2) is satisfied too. However, the saturation of the SESAM, i.e., the value of the factor $S = E_p/F_{\text{sat},A} A_{\text{eff},A}$ should always be kept below 20 to avoid multiple pulsing instabilities and damage to the SESAM.^{8,9} By properly choosing the pumping focusing optics and the cavity mirrors we were able to some extent to achieve the proper values of $A_{\text{eff},L}$ and $A_{\text{eff},A}$ so that all the previous conditions were simultaneously met. Thus, for the case of a 1.2-MHz system, i.e., for $P = 470 \text{ mW}$ with a 10% output coupler corresponding to $E_p = 3.5 \mu\text{J}$ for a double pass (under strong overlapping of the beams) through the Nd:YVO₄ crystal, i.e., $F_{\text{sat},L} = h\nu/4\sigma_L = 30 \text{ mJ/cm}^2$ and for a SESAM with $\Delta R = 6.1\%$ and $F_{\text{sat},A} = 70 \text{ mJ/cm}^2$

we chose a 1:1 two-lens focusing of the pump beam, providing a mode area in the crystal estimated to be approximately $A_{\text{eff},L} = 1.3 \times 10^{-3} \text{ cm}^2$ (pump fiber core diameter, 400 μm) and a 2-m focusing mirror on the SESAM providing a 770- μm mode diameter on the SESAM, corresponding to $A_{\text{eff},A} = 4.7 \times 10^{-3} \text{ cm}^2$. For the above values condition (2) is well satisfied, since $3.5 > 0.88$ and the saturation of the SESAM is $S = 10$.

In conclusion, operation of an ultralow-repetition-rate (lower than 1 MHz), mode-locked Nd:YVO₄ oscillator has been demonstrated with a simple and low-cost design. Stable long-term operation at 1.2 MHz with a pulse duration of 16.3 ps and 24-kW peak power was achieved. To the best of our knowledge this is the lowest repetition rate ever reported for a completely passively mode-locked laser with no use of complicated and expensive techniques such as cavity dumping. In preliminary experiments on frequency doubling, conversion efficiency into 532 nm as high as 50% was achieved with the use of 10-mm-long periodically poled KTP crystal. These results are promising for the further use of this source for the generation of short visible pulses for fluorescence lifetime measurements.

This research was partially supported by the research program POLA from the Contrat Plan Etat Région (2000–2006) (French State and Conseil Général de l'Essonne). D. N. Papadopoulos worked on this project under a Marie Curie fellowship. S. Forget's e-mail address is sebastien.forget@iota.u-psud.fr.

*Present address, Lasers and Applications Group, Department of Physics, National Technical University of Athens, Heron Polytechniou 9, 15780 Athens, Greece.

References

1. S. Forget, F. Balembos, G. Lucas-Leclin, and P. Georges, *Opt. Commun.* **220**, 187 (2003).
2. A. Herriott, H. Kogelnik, and R. Kompfner, *Appl. Opt.* **3**, 523 (1964).
3. S. H. Cho, F. X. Kärtner, U. Morgner, E. P. Ippen, J. G. Fujimoto, J. E. Cunningham, and W. H. Knox, *Opt. Lett.* **26**, 560 (2001).
4. U. Keller, D. A. B. Miller, G. D. Boyd, T. H. Chiu, J. F. Ferguson, and M. T. Asom, *Opt. Lett.* **17**, 505 (1992).
5. U. Keller, K. J. Weingarten, F. X. Kärtner, D. Kopf, B. Braun, I. D. Jung, R. Fluck, C. Hönninger, N. Matuschek, and J. Aus der Au, *IEEE J. Sel. Top. Quantum Electron.* **2**, 453 (1996).
6. F. Krausz, M. E. Fermand, T. Brabec, P. F. Curley, M. Hofer, M. H. Ober, C. Spielmann, E. Winter, and A. J. Schmidt, *IEEE J. Quantum Electron.* **28**, 2097 (1992).
7. C. Hönninger, R. Paschotta, F. Morier-Genoud, M. Moser, and U. Keller, *J. Opt. Soc. Am. B* **16**, 46 (1999).
8. G. J. Spühler, T. Südmeyer, R. Paschotta, M. Moser, K. J. Weingarten, and U. Keller, *Appl. Phys. B* **71**, 19 (2000).
9. F. X. Kärtner, J. Aus der Au, and U. Keller, *IEEE J. Sel. Top. Quantum Electron.* **4**, 159 (1998).