Passively Q-switched Nd:GdVO$_4$ solid-state lasers with stabilized repetition rates

Haifeng Pan (潘海峰) and Heping Zeng (曾和平)

Key Laboratory of Optical and Magnetic Resonance Spectroscopy, and Department of Physics,
East China Normal University, Shanghai 200062

Received February 23, 2005

By modulating the pump current, we developed a passively Q-switched diode-pumped all-solid-state laser with a repetition rate stabilized up to 10^{-7}. It was experimentally demonstrated that the stability could sustain for an arbitrarily long time. Moreover, the stabilized repetition rates which were synchronized with different modulating frequencies were tuneable in a wide range, by adjusting the period of the pumping cycle only. The output single-pulse energy was also stabilized, which was independent on the pump power after reaching a saturable value.

OCIS codes: 140.3480, 140.3540, 140.3580, 140.5680.

Pulsed solid-state lasers in the near infrared region were of a growing interest due to their potential applications in the scientific, medical, industrial, and military systems[1,2]. Especially, passively Q-switched diode-pumped solid-state lasers could offer good compactness and robustness that were well-matched to a variety of applications such as micro-surgeon, laser ranging, injecting seeds for amplifiers, remote sensing, and so forth[3,4]. It was well-known that the laser repetition frequency was a crucial parameter in all the applications mentioned above. Passively Q-switched lasers could be conveniently operated by using intracavity saturable absorbers such as Cr^{4+}:YAG crystals to compose all-solid-state, compact, simple, and low-cost pulsed lasers. Since Cr^{4+}:YAG crystal has a saturable absorption band from 0.9 to 1.2 μm, it was widely employed as a suitable saturable absorber in passively Q-switched lasers at 1.06 μm without the need of high-voltage or radio frequency (RF) drivers. The pulse repetition rates of passively Q-switched lasers ranged from a few hundred Hz to several MHz with intracavity Cr^{4+}:YAG crystals as saturable absorbers[5−7]. As a disadvantage which seriously limits performances of the passively Q-switched lasers, however, instabilities up to 10% of the repetition frequency were always observed, mainly due to the environmental fluctuations, the thermal gradients in the active media, or the shifts of the diode pump power and spectrum. As well known, in passively Q-switching processes, the period between two adjacent pulses corresponded to the time needs for population inversion to recuperate its threshold value, which was directly governed by the pump power. In the passively Q-switching process, pump power was the only accessible parameter that can be conveniently adjusted to improve the stability of the repetition rates of the passively Q-switched lasers. In order to obtain an emitted pulse chain with a stabilized repetition rate, a simple method has been proved effective and robust by modulating the pump current of the pump laser diode, which forced a synchronization of the Q-switched laser pulse chain with the modulating frequency. Lai *et al.* have experimentally demonstrated the feasibility of this kind of synchronization[8]. Recently, Nd:GdVO$_4$, as a novel laser active material, has attracted great attention due to its excellent physical, optical, and mechanical properties[9−11]. Nd:GdVO$_4$, the active medium used in our experiments, exhibiting its large absorption cross section (5.2×10^{-19} cm^2)[12] and excellent thermal conductivity[13], is very suitable for obtaining high-power lasers[14]. The excellent thermal conductivity of Nd:GdVO$_4$ reduced the disturbance due to thermal effects in the laser crystal, such as the thermal birefringence[15] and so forth, and consequently ensured stable laser operation. In this paper, we report on a typical passively Q-switched diode-pumped Nd:GdVO$_4$ all-solid-state laser, with intracavity Cr^{4+}:YAG employed as the saturable absorber, of which pump current was modulated to achieve the stabilization of its repetition rate. As shown in our experiments, a wide tunable range of stabilized repetition rate was obtained by changing the modulation parameter of the pump source, such as pump current, the modulation frequencies, and the duty-cycle of the modulation period. At the same time, the single-pulse energy and the pulse peak power could sustain in a reasonable range when the modulating frequency was changed. Compared with actively Q-switched lasers, our pulsed laser could be operated to output pulses with very stable single-pulse energy and repetition rate while the complexity of the system could be reduced. Remarkably, as the involved technique is very simple, it is easy to achieve experimentally. Therefore, it was proved as an effective way to obtain stabilized pulse train in the passively Q-switched lasers, which could extend the passively Q-switched laser into wide applications.

The experimental setup of the laser cavity structure is schematically given in Fig. 1. The laser resonator was composed of a concave mirror M_1 ($R = 50$ mm) with anti-reflection coating at 808 nm on both sides and high-reflection coating at 1064 nm on the concave side, and a plane output coupler M_2 with a transmission of 5% at 1064 nm. The total cavity length was approximately 30 mm. A 1-mm-thick, 1.0 at.-% doped a-cut Nd:GdVO$_4$ crystal was employed as the active medium, which had antireflection coatings at 808 and 1064 nm on both sides. A piece of Cr^{4+}:YAG crystal with antireflection

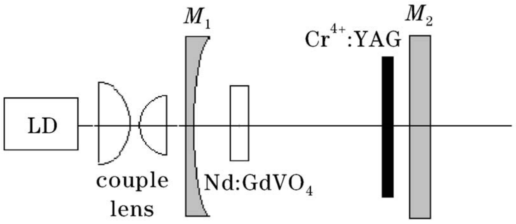

Fig. 1. Cavity configuration of the passively Q-switched Nd:$GdVO_4$ lasers.

coatings at 1064 nm on both sides was inserted into the laser resonator as the intracavity saturable absorber. And the small-signal transmission of the Cr^{4+}:YAG crystal was 90%. The pump source was a 1.6-W continuous wave (CW) laser diode, and the coupling efficiency was measured to be 80%. In order to maintain the emission wavelength of the diode at 808 nm, laser diode was controlled to 26 °C together with Nd:$GdVO_4$ crystal inside the cavity. The Cr^{4+}:YAG crystal was placed closely next to the output coupler mirror. An InGaAs Pin detector (Newport 818-BB-30) photodiode and an oscilloscope (500 MHz, HP-54616C) were used to record the output laser pulses. The pump modulation was offered by a function waveform generator (Aglient, 33250A) in square waveform whose duty-cycle and period could be adjusted conveniently.

Without modulation, the threshold of our passively Q-switched laser was at the diode pump current of 1.2 A, corresponding to the effective incident pump power of 520 mW. As the pump current increased, the repetition rate of the passively Q-switched pulse train rose approximately from 3 to 8.6 kHz. At the pump power of 1.2 W for instance, an average output power of 21.5 mW with a repetition rate of 6.15 kHz was observed, corresponding to the single-pulse energy around 3.5 μJ and the pulse-width about 19 ns. The pulse train as well as the pulse profile was recorded and displayed in Fig. 2. Due to the environmental influence, a drastic drift of the repetition rate was observed even under a constant pump power, which was up to 20% during several minutes and 5% in less than 1 second. A little more stable repetition rate could be obtained in our passively Q-switched laser, if the mechanical vibration of the resonator as well as the temperature-control to the Cr^{4+}:YAG crystal was improved.

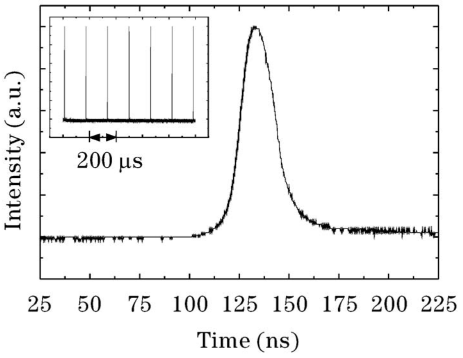

Fig. 2. The Q-switched pulse profile when the repetition rate was unstabilized. Inset shows the corresponding pulse train with the repetition rate of 6.15 kHz approximately.

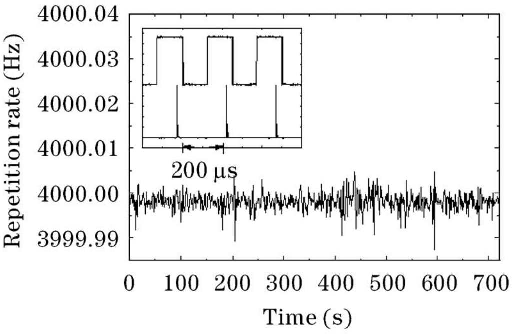

Fig. 3. The stability of the repetition rate in 720 seconds, and the inset shows the synchronization at a repetition rate of 4 kHz between the modulation frequency and the emitting pulse train.

As shown in the inset of Fig. 3, an improved stability of the output pulse chain could be achieved when the pump current was modulated. In our experiments, the amplitude of the pump current was fixed at 1.9 A, and the modulation depth was 100%. The modulation trigger signal in square waveform was from a function waveform generator with a 4-kHz frequency and a 50% duty-cycle. As a result, the emitting pulse repetition rate was synchronous with the modulation frequency of the pump power. In spite of the influence from the environment, a stable train of the passively Q-switched pulse was obtained with a high stability of the repetition rate up to 10^{-7}, as shown in Fig. 3. Moreover, this stability could sustain for an arbitrarily long time. The pulse width was measured to be 17.5 ns and the corresponding single-pulse energy was calculated to be 3.25 μJ. The average output power showed little evidence of fluctuating, indicating that the repetition rate was stabilized well.

The principle of the synchronization could be simply explained as follows. The passively Q-switching could only occur during the pumping cycle with a time delay inherently determined by the gain medium and saturable absorber and by the geometric configuration of laser cavity as well. In our experiment, the time lag between the rising edge of the pump period and Q-switched pulse was contributed both by the response time of the laser diode and the characteristic delay of the passively Q-switching process. The response time of the laser diode determined by the inherent properties of the diode and the power supply circuit, kept almost constant during the whole experiment. At the beginning of the passive Q-switching process, the intracavity intensity and the population inversion increased up to a threshold value, and then a laser pulse was released. But because of the pump modulation, the pump current fell down promptly after the laser pulse was released to prevent the generation of the second pulse, so that an exact synchronization of the Q-switching with the pump modulation would be followed. And during one pump period, there was only one Q-switched laser pulse released. Before the next pump period, there was enough time for the gain material to recover to its initial state. When the next pumping period began, the process repeated. Since the initial condition of laser before each pumping cycle was exactly the same, the corresponding time lag remained the same. Therefore, the repetition rate of the Q-switched laser pulse was stably synchronous with the pump modulation. If the pumping duration was excessively long, the population inversion would be raised up to its threshold value for more than one time, and the multiple pulses would come out during one pump cycle. As a result, an asymmetrical pulse train with unstable repetition rate would appear, whereas the time lag for the first pulse stayed unchanged.

In passive Q-switching processes, the single-pulse energy would rise with the pump power under low pump conditions, and then became saturated at a maximum value when the pump power increased to a sufficiently high value. Further increase of the pump power only resulted in the shortening of the time lag and the period between two adjacent pulses within one pump cycle. When the pump power was low, the time lag was still stable though the single-pulse energy had not reached its maximum value. In order to get optimized laser performances, the pump power was fixed to ensure the single-pulse laser up to its saturated energy. When the pump power increased, the time lag was shortened as well. If the pumping duration was not adjusted correspondingly to the shortened time lag, the multiple pulses would emerge during one pumping cycle, and consequently the synchronization would be broken. The physical images of the process were clearly displayed in our experimental results.

As shown in Fig. 4, the stable time lag was approximately 100 μs, when the trigger signal frequency and the amplitude of the pump current were 4 kHz and 1.9 A, respectively. With the pump duration shorter than 97.5 μs, no pulse emission was observed. And the stable time lag was obtained when the pump pulse duration was longer than 105 μs. If the pumping cycle was further lengthened above 168 μs, multiple pulses would appear within one pump cycle, as shown in the inset of Fig. 4, and the output power increased rapidly. Figure 5 shows the dependences of the single-pulse energy and the time lag on the incident pump power. The repetition rate and the duty-cycle were 4 kHz and 66%, respectively. Obviously, the single-pulse energy became saturated when the pump power was beyond 1.15 W, and reached its saturated value of ~3.5 μJ. With the increase of pump power, the time lag was shortened in the whole process. Multiple pulses similar to those shown in the inset of Fig. 4 appeared when pump power was higher than 1.25 W.

In order to achieve the synchronization with different modulation frequencies, the duty-cycle of the modulation was tuned. The amplitude of the pump current was set at 1.9 A, therefore, the time lag remained still 100 μs. The pumping duty-cycle varied from 30% to 80% to achieve the synchronization with a repetition rate from 3 to 7.8 kHz, respectively. As shown in Fig. 6, the output single-pulse energy drifted slightly when the laser operated with different repetition rates[16]. In the mean time, no matter how the repetition rate varied, the repetition stabilities always maintained as high as 10^{-7}. If the modulating frequency was decreased below 3 kHz, the synchronization could hardly follow, which was in close agreement with the range measured when the repetition rate was unstabilized.

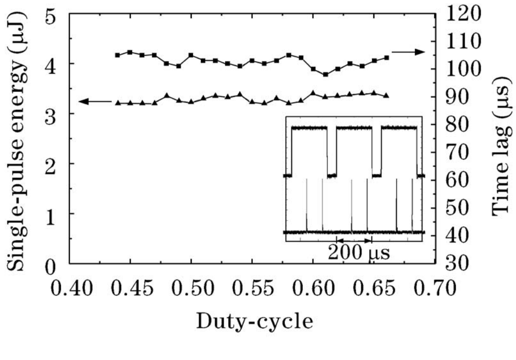

Fig. 4. The dependences of the single-pulse energy and the time lag on the duty-cycle when the repetition rate was 4 kHz. Inset shows multiple pulses appearing when the pump duration was 175 μs.

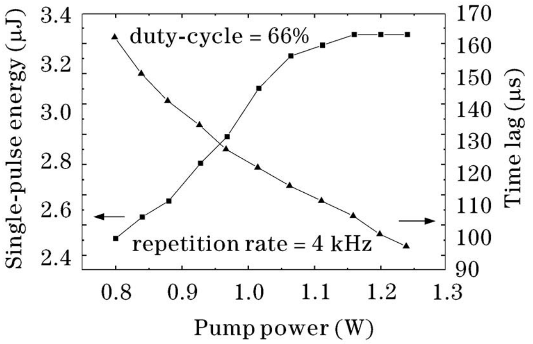

Fig. 5. The single-pulse energy and time lag as functions of the incident pump power when the repetition rate was 4 kHz.

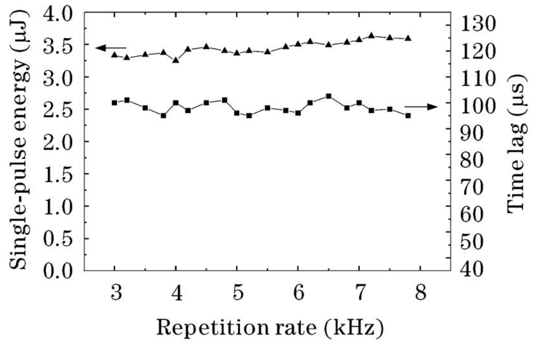

Fig. 6. The dependences of the single-pulse energy and the time lag on the stabilized repetition rate.

In conclusion, we developed a simple technique for stabilizing the repetition rate of a passively Q-switched diode-pumped all-solid-state Nd:GdVO$_4$ laser. By modulating the pump current of the laser diode, the synchronization between the pumping modulation and laser pulse emission was achieved in our experiment. High stability of repetition rate of the Q-switched laser pulse was obtained for an arbitrarily long timescale. In spite of the influences from environment and the mechanical vibration of the resonator, the repetition stability reached up to 10^{-7} in amplitude. Furthermore, a wide tunable range of stabilized repetition rate was obtained by alternating the duty-cycle and the repetition of the modulation, without needs of changing the pump current value or any other parameter. It has also been proved that the off-axially cut or the c-cut crystal could support shorter pulse width and higher single-pulse energy[17,18]. Thus, it is predicted that the performances, such as output power, pulse width, single-pulse energy, and so forth, can be improved in similar repetition-rate-stabilized passively Q-switched solid-state lasers.

This work was partly supported by the Shanghai Priority Academic Discipline, the National Key Project for Basic Research (No. TG1999075204), and the National Natural Science Foundation of China (No. 10374028). H. Zeng is the author to whom the correspondence should be addressed, his e-mail address is hpzeng@phy.ecnu.edu.cn.

References

1. J. J. Zayhowski and C. Dill III, Opt. Lett. **19,** 1427 (1994).
2. Y. Shimony, Z. Burshtein, and Y. Kalisky, IEEE J. Quantum Eletron. **31,** 1738 (1995).
3. J. J. Zayhowski, Rev. Laser Eng. **26,** 841 (1998).
4. A. V. Jelalian, *Laser Radar Systems* (Artech House, Boston, MA, 1992).
5. S. Li, S. Zhou, P. Wang, Y. C. Chen, and K. K. Lee, Opt. Lett. **18,** 203 (1993).
6. R. S. Afzal, A. W. Yu, J. J. Zayhowski, and T. Y. Fan, Opt. Lett. **22,** 1314 (1997).
7. A. Agnesi, S. Dell'Acqua, and G. C. Reali, Opt. Commun. **133,** 211 (1997).
8. N. D. Lai, M. Brunel, F. Bretenaker, and A. L. Floch, Appl. Phys. Lett. **79,** 1073 (2001).
9. C. Czeranowsky, M. Schmidt, E. Heumann, G. Huber, S. Kutovoi, and Y. Zavartsev, Opt. Commun. **205,** 361 (2002).
10. J. Liu, C. Wang, C. Du, L. Zhu, H. Zhang, X. Meng, J. Wang, Z. Shao, and M. Jiang, Opt. Commun. **188,** 155 (2001).
11. J. Liu, J. Yang, and J. He, Opt. Commun. **219,** 317 (2003).
12. T. Jensen, V. G. Ostroumov, J. P. Meyn, G. Huber, A. I. Zagumennyi, and I. A. Shcherbakov, Appl. Phys. B **58,** 373 (1994).
13. P. A. Studennikin, A. I. Zagumennyi, Y. D. Zavartsev, P. A. Popov, and I. A. Shcherbakov, Quantum Electron. **25,** 1162 (1995).
14. J. Liu, J. Yang, F. Liu, and J. L. He, Chin. Opt. Lett. **1,** 337 (2003).
15. H. Pan, S. Xu, and H. Zeng, Opt. Express **13,** 2755 (2005).
16. J. A. Morris and C. R. Pollock, Opt. Lett. **15,** 440 (1990).
17. S. Zhang, E. Wu, and H. Zeng, Opt. Commun. **231,** 365 (2004).
18. H. Chen, E. Wu, and H. Zeng, Opt. Commun. **230,** 175 (2004).