Repetition rate control in continuous-wave-pumped, passively Q-switched solid-state lasers

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Abstract. We describe a technique for the adjustment and control of repetition rates in continuous-wave-pumped, passively Q-switched solid-state lasers. The method uses a movable intracavity lens to modify the mode matching and hence the gain of the laser beam per pass. The technique was applied to a diode-pumped $\text{Nd}^{3+}:\text{YVO}_4$ laser passively Q-switched with a $\text{Cr}^{4+}:\text{YAG}$ saturable absorber at 1064 nm. At a fixed pump power of 5.4 W, we were able to continuously adjust the repetition rate between 13.8 and 25 kHz by translating an intracavity converging lens. We also demonstrate that by adjusting the lens position, the repetition rate can be kept at a desired value as the pump power varies. In particular, as the pump power was increased from 3.95 to 5.9 W, the lens position was varied by 0.91 cm to keep the repetition rate constant at 13.8 kHz. Rate-equation formalism was used to investigate the variation of the repetition rate as a function of lens position, and very good agreement was obtained between experiment and theory. © 2007 Society of Photo-Optical Instrumentation Engineers. [DOI: 10.1117/1.2709857]

Subject terms: solid-state lasers; passively Q-switched lasers; saturable absorbers; neodymium lasers; repetition rate in passively Q-switched lasers.

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1 Introduction

Over recent decades, considerable effort has been focused on the development of passively Q-switched solid-state lasers. In comparison with their actively Q-switched counterparts, passively Q-switched lasers offer the advantage of simpler system architecture and reduced cost, since all-optical pulse shaping occurring inside the saturable absorber obviates the need for sophisticated electronics. Practical saturable absorbers suitable for passive Q-switching of solid-state lasers come in various forms. Examples include transition metal ion-doped crystals such as Cr^{4+} -doped garnets¹ or silicates,² and semiconductor saturable absorbing mirror structures commonly referred to as SESAMs,³ among others. In all cases, the absorption of the saturable absorber decreases with increasing intensity, and if the second threshold condition is satisfied, a periodic train of pulses is generated from the resonator.^{4,5} To date, various aspects of passively Q-switched solid-state lasers have been explored. As an example, output pulse energies in excess of 100 mJ have been demonstrated in 1064-nm Nd:YAG lasers repetitively Q-switched with $\text{Cr}^{4+}:\text{YAG}$ crystals.⁶ In other studies, continuous-wave-pumped, passively Q-switched microchip lasers have been reported,⁷⁻¹⁰ generating subnanosecond pulses¹⁰ as short as 37 psec.

Let us consider continuous-wave-pumped, passively Q-switched solid-state lasers. An important issue that needs to be addressed in the design of practical systems has to do with the control of the pulse repetition rate. In general, the pulse repetition rate will depend on an interplay of many factors, including steady-state power gain in the laser crys-

tal, passive losses of the resonator, small-signal loss of the saturable absorber, possibility of excited-state absorption, and the fluorescence lifetime of the gain medium. Factors such as absorption/emission cross sections, passive losses, small-signal loss of the saturable absorber, or fluorescence lifetime will be fixed for a particular choice of gain medium and saturable absorber. However, the power gain per pass inside the laser crystal will depend on the level of pumping and hence can cause undesirable variations in the pulse repetition rate as the pump power is changed. It is therefore important to devise a technique to control the pulse repetition rate against variations in the pump power.

In this paper, we propose a simple scheme for the control of the repetition rate in a continuous-wave pumped, passively Q-switched solid-state laser by using a movable intracavity lens. As the lens is translated inside the cavity, mode matching and hence the gain per pass will vary, and the repetition rate can be continuously adjusted. The technique can be used for two different applications: for adjusting the repetition rate of the laser at a constant pump power or for controlling the repetition rate at a desired value as the pump power changes. We have demonstrated the usefulness of this method for both cases in a diode-pumped $\text{Nd}^{3+}:\text{YVO}_4$ laser passively Q-switched with a $\text{Cr}^{4+}:\text{YAG}$ saturable absorber at 1064 nm. At an incident diode power of 5.4 W, we were able to continuously adjust the repetition rate of the laser between 13.8 and 25 kHz. In a second experiment, we showed how the location of the lens should be varied to keep the repetition rate fixed at 13.8 kHz, as the pump power varies from 3.95 to 5.9 W. Finally, we used rate-equation formalism to model the variation of the repetition rate with lens position and obtained very good agreement between theory and experiment.

Fig. 1 Schematic of the diode-pumped passively Q-switched $\text{Nd}^{3+}:\text{YVO}_4$ laser.

2 Experimental Setup and Results

A schematic of the experimental setup is shown in Fig. 1. The gain medium was a $3 \times 3 \times 10$ mm piece of *a*-cut $\text{Nd}^{3+}:\text{YVO}_4$ crystal with 0.5 at. % Nd concentration. The crystal was wrapped in tin foil and clamped inside a copper block maintained at 18°C by water cooling. The first surface (S_1) was coated to have high transmission at 809 nm and high reflection at 1064 nm, and the second surface (S_2) was antireflection (AR)-coated at 1064 nm. The resonator had a total length (d_T) of 15.2 cm and was terminated with a flat 2.2% transmitting output coupler (OC). An intracavity lens (L1), AR-coated at 1064 nm, was positioned near the center of the cavity. The focal length of the lens was 10 cm. The distance of the lens from the output coupler- (d_f) could be changed during the experiments by using a translation stage. Passive Q-switching was obtained by placing a 1.56-mm-long normal-cut AR-coated $\text{Cr}^{4+}:\text{YAG}$ saturable absorber (SA) near the output coupler of the resonator. The small-signal transmission of the $\text{Cr}^{4+}:\text{YAG}$ crystal was 80% at 1064 nm. No attempt was made to control the temperature of the $\text{Cr}^{4+}:\text{YAG}$ crystal since previous studies showed that the saturation characteristics during pulsed excitation are independent of temperature¹¹ between -60 and 90°C . The resonator was end-pumped by a diode-array (D) at 806 nm. The diode output was coupled via a $1550\text{-}\mu\text{m}$ -diam fiber bundle and external pump focusing optics (PF) were used to focus the diode output to a beam waist of $287\text{ }\mu\text{m}$ inside the $\text{Nd}^{3+}:\text{YVO}_4$ crystal. The M^2 of the pump beam was measured to be 275. In the experiments, the cw power performance of the $\text{Nd}^{3+}:\text{YVO}_4$ laser was first characterized up to an incident pump power of 9.6 W, at which level as high as 1.43 W of cw output power could be obtained. Here, the intracavity lens was at a distance of $d_f=9.5$ cm from the output coupler. The incident threshold pump power and the slope efficiency were measured to be 0.3 W and 16%, respectively.

In order to initiate passive Q-switching, the $\text{Cr}^{4+}:\text{YAG}$ saturable absorber was placed near the output coupler, as shown in Fig. 1. Near lasing threshold, an output power of 34 mW could be obtained with 3.05 W of incident pump power. Once above lasing threshold, a train of Q-switched pulses could be readily obtained. However, for the case

Fig. 2 Variation of the repetition rate as a function of the input pump power at a fixed position of the intracavity lens.

Fig. 3 Measured variation of the (a) repetition rate, (b) output pulse width, and (c) average output power with lens position at the input pump power of 5.4 W.

where the intracavity lens position was fixed, the repetition rate and the pulse width of the output pulses varied with the incident pump power. Figure 2 shows the measured variation of the repetition rate as a function of the incident pump power. In these measurements, d_f was set to 9.5 cm. As the pump power is increased from 3.05 to 7.29 W, the repetition rate varied between 3.5 and 18.2 kHz. In the same pump power range, the pulse width remained near 45 ns.

In the next set of measurements, we demonstrated the use of the intracavity lens in continuously adjusting the repetition rate of the laser. Here, the diode pump power was kept constant at 5.4 W, and the intracavity lens was translated from $d_f=8.5$ cm to $d_f=9.5$ cm. As can be seen in Fig. 3(a), the repetition rate of the laser could be continuously varied from 25 to 13.8 kHz. We note that as the intracavity lens is translated, the spot sizes inside the gain medium and the saturable absorber both change and could lead to variations in the output pulse energy and output pulse width. In order to investigate this further, we also measured the dependence of the output pulse width [Fig. 3(b)] and the average output power [Fig. 3(c)] on the intracavity lens position. As can be seen in Fig. 3(b), when the intracavity lens was translated from $d_f=8.5$ cm to $d_f=9.5$ cm, the output pulse width decreased from 100 to 44 ns. Standard ABCD analysis of the cavity shows that when d_f is increased from 8.5 to 9.5 cm, the average spot size on the saturable absorber decreases from 145 to $108\text{ }\mu\text{m}$, while the spot size inside the gain medium increases from 229 to $323\text{ }\mu\text{m}$. The observed trend in the pulse width can be explained by noting that as the spot size on the saturable absorber decreases, stronger bleaching takes place. This further leads to faster build-up of the intracavity power and faster extraction of the stored energy, hence giving shorter output pulses. Furthermore, as can be seen in Fig. 3(c), the average output power increased from 43 to 158 mW due to the translation

Fig. 4 Variation of the intracavity lens position required to keep the repetition rate constant (13.8 kHz) at different input pump power levels.

of the lens, resulting in an increase of the corresponding energy per pulse from 1.7 ($d_f=8.5$ cm, repetition rate = 25 kHz) to 11.4 μJ ($d_f=9.5$ cm, repetition rate = 13.8 kHz). Here, a qualitative explanation may be offered by examining how the mode area in the gain medium and the fractional power gain are modified by the intracavity lens position. We discuss this further in Sec. 3, after the repetition rate calculations.

The intracavity lens can also be used to stabilize the repetition rate at a fixed value as the pump power varies. As an example, Fig. 4 shows how the position of the lens must be adjusted in order to keep the repetition rate at 13.8 kHz for different diode pump power levels. As the pump power was increased from 3.95 to 5.9 W, the lens position was varied by 0.91 cm to keep the repetition rate fixed at 13.8 kHz. This set of data can be used to actively control the repetition rate of the laser against small power fluctuations by introducing a closed loop servo system to drive the lens. The latter was not taken up in the present study. At all pump power levels used, the output pulsewidth remained below 80 ns.

3 Analysis of the Repetition Rate Data

Rate equation formalism can be used to analyze the effect of the intracavity lens on the repetition rate of the cw passively Q-switched solid-state lasers. Once a Q-switched pulse depletes the gain and leaves the cavity, the next one starts building up from noise. After a sufficient pumping time, the accumulated gain becomes equal to the total unsaturated loss of the resonator, and pulse shaping again commences. Spuhler et al.¹⁰ showed that the pulse repetition rate f_{rep} , which is the inverse of the time between consecutive pulses, can be calculated accurately from:

$$f_{rep} = \frac{g_0 - (L + q_0)}{\Delta g \tau_f}, \quad (1)$$

where g_0 is the steady-state single-pass fractional power gain, τ_f is the fluorescence lifetime of the gain medium, L is the single-pass nonsaturable cavity loss, q_0 is the single-pass small-signal loss of the saturable absorber, and Δg is the difference between the threshold gain g_{th} ($g_{th}=L+q_0$) and the final depleted gain g_f . g_{th} is the minimum gain needed for the pulse to see a net gain in each round-trip. In our case, $q_0=0.2$. Loss analysis of the cw laser showed that L is about 0.02. Therefore, we neglected L in relation to g_0

Fig. 5 Variation of the calculated and measured repetition rate as a function of lens position at the input pump power of 5.4 W.

in repetition-rate calculations. Also, the final depleted gain was assumed to be negligible, giving $f_{rep} \approx (g_0 - q_0)/q_0 \tau_f$.

As can be seen from the preceding, f_{rep} depends on the steady-state single-pass gain g_0 , which is influenced by several parameters, including the stimulated emission cross section of the gain medium, fluorescence lifetime, pump power, and the degree of overlap between the pump and the laser modes. In the case of the resonator with the intracavity lens, as the lens is translated, the laser spot size distribution and hence the mode overlap between the pump and laser beams will vary. This affects the single-pass power gain g_0 . For a given pump and laser spot size distribution in the gain crystal, we can determine g_0 by solving for the spatial evolution of the intracavity laser power. Neglecting saturation effects at the lasing wavelength, the power P_L^+ of the forward-moving beam satisfies the differential equation¹²:

$$\frac{1}{P_L^+} \frac{dP_L^+}{dz} = g_T \int_0^\infty dr 2\pi r \left[\frac{\Phi_L \Phi_p P_p \exp(-\alpha_{p0} z)}{I_{sa}} \right] / \left[1 + \frac{P_p \exp(-\alpha_{p0} z) \Phi_p}{I_{sa}} \right]. \quad (2)$$

Here, P_p is the incident pump power, I_{sa} is the absorption saturation intensity, α_{p0} is the differential pump absorption coefficient, g_T is the maximum extractable small-signal gain coefficient, and Φ_L and Φ_p are the respective normalized Gaussian transverse intensity distributions for the laser and pump beams. Pump and laser spot size functions were determined from standard ABCD analysis. For each setting of the intracavity lens location, we determined the spot size distribution of the laser beam and calculated the single pass gain g_0 from:

$$g_0 = \frac{P_L^+(L_0) - P_L^+(0)}{P_L^+(0)}. \quad (3)$$

The corresponding repetition rate was then calculated from Eq. (1). The stimulated emission cross section σ_e and the waist location z_{fp} of the pump were used as fitting parameters. Figure 5 shows the measured variation and the best-fit calculation for f_{rep} as a function of d_f . (The fixed parameters of the calculation were: diode pump power=5.4 W, $d_T=15.2$ cm, $L_0=10$ mm, crystal refractive index=1.165, focal length of the lens=10 cm, reflectivity of the output coupler=97.9%, $\omega_{p0}=287$ μm , $M^2(\text{pump})=275$, fluores-

cence lifetime = 95 μs , and $\alpha_{p0} = 221.36 \text{ m}^{-1}$.) Very good agreement was obtained between theory and experiment for the best-fit values of 0.0016 m and $7.7 \times 10^{-23} \text{ cm}^2$ for z_{fp} and σ_e , respectively. This value of σ_e is in good agreement with what was previously determined from cw efficiency data in Ref. 12. We note in passing that the technique discussed here can also be used as an alternative method for the determination of the stimulated emission cross section of a solid-state laser material from the repetition-rate data when operated in cw-pumped, passively Q-switched mode.

Finally, we return to Fig. 3(c) to provide a qualitative explanation for the observed trend in the output power as a function of the intracavity lens position. If the residual gain after the passage of the pulse is negligible, the output pulse energy is approximately proportional to $g_0 A_{eff}$, where A_{eff} is the effective mode area in the gain medium.¹⁰ Calculation of g_0 was described earlier. By using the best-fit values for z_{fp} and σ_e , we find that g_0 decreases from 0.62 to 0.44 as d_f is changed from 8.5 to 9.5 cm. However, at the same time, the average mode radius inside the gain medium increases from 229 to 323 μm , giving a larger mode area and resulting in the observed net increase in the output energy per pulse from 1.7 to 11.4 μJ .

4 Conclusions

We have discussed a technique for the adjustment and control of repetition rates in cw-pumped, passively Q-switched solid-state lasers. The method uses a movable intracavity lens to modify the mode matching and hence the gain of the laser beam per pass. The technique was applied to a diode-pumped $\text{Nd}^{3+}:\text{YVO}_4$ laser passively Q-switched with a $\text{Cr}^{4+}:\text{YAG}$ saturable absorber at 1064 nm. At a fixed pump power of 5.4 W, we were able to continuously adjust the repetition rate between 13.8 and 25 kHz by translating an intracavity converging lens. We also demonstrated that the lens position can be adjusted to keep the repetition rate at a desired fixed value as the pump power changes. Finally, we used a rate-equation model to investigate how the repetition rate varies with lens position and obtained very good agreement between experimental results and theory. The technique discussed in this paper can be readily applied to the stabilization of the repetition rate by incorporating a closed-loop servo circuit. In the case of microchip passively Q-switched solid-state lasers, the gain crystal itself could be translated to vary the pump focusing, which affects the gain per pass and the repetition rate.

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