Simultaneous Q-Switching and Mode-Locking in a Diode-Pumped $Nd:YVO_4$–$Cr^{4+}:YAG$ Laser

Yung-Fu Chen and S. W. Tsai

***Abstract*—Parametric studies of passive *Q*-switching and mode-locking in a $Nd^{3+}:YVO_4$–$Cr^{4+}:YAG$ laser were theoretically carried out. Simultaneous mode-locking and *Q*-switching was also experimentally studied. It was found that over 90% of the output power could be mode-locked in a diode-pumped passively *Q*-switched $Nd^{3+}:YVO_4$–$Cr^{4+}:YAG$ laser. The average pulse duration of the mode-locked pulse train was estimated to be around $110 \sim 150$ ps. The highest peak power of a single pulse near the maximum of the *Q*-switched envelope was greater than 100 kW.**

***Index Terms*—$Cr^{4+}:YAG$, diode-pumped, mode-locked, $Nd^{3+}:YVO_4$, passively *Q*-switched.**

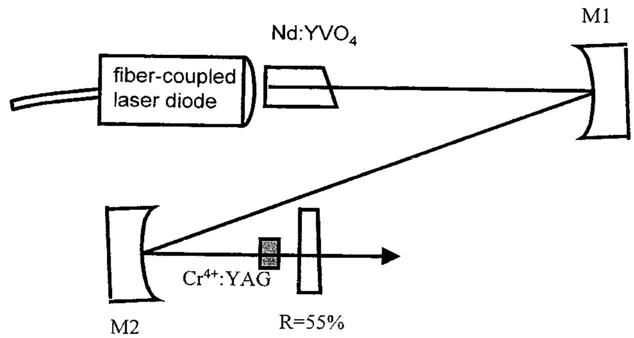

Fig. 1. Configuration of passively Q-switched mode-locked $Nd:YVO_4$ laser.

I. Introduction

In THE LAST few years, a number of neodymium-doped vanadium-based crystals have been identified as promising materials for diode pumped lasers, particularly yttrium orthovanadate (YVO_4) and gadolinium orthovanadate ($GdVO_4$) [1]. Several advantages over Nd:YAG crystals include a larger emission cross-section, a pump power threshold, a wider absorption bandwidth, and a polarized output. For example, the wider absorption bandwidth means that the laser output power is less sensitive to drifting of the diode pump wavelength due to a change of temperature or aging. The linearly polarized laser output is beneficial not only to nonlinear wavelength conversion, but also to avoiding undesired birefringent effects.

Chromium-doped yttrium aluminum garnet ($Cr^{4+}:YAG$) provides a large absorption cross section in the $0.9 \sim 1.2$ μm spectral region, which makes it an attractive choice as a passive Q-switch for Nd-doped lasers [2]–[4]. It is, however, usually difficult to operate a diode-pumped, passively Q-switched $Nd:YVO_4$ laser with $Cr^{4+}:YAG$ as the saturable absorber. The main difficulties arise from the fact that a $Nd^{3+}:YVO_4$ crystal has a high stimulated emission cross section. For good passive Q-switching, absorption saturation in the absorber must occur before gain saturation in the laser crystal (the second threshold condition) [5]. Therefore, a cavity is required that has a small beam area in the $Cr^{4+}:YAG$ crystal. Even though passively Q-switched $Nd^{3+}:YVO_4$ and $Nd^{3+}:GdVO_4$ lasers have been demonstrated [6], [7], the output pulse energy and peak power are obviously lower than those of $Nd^{3+}:YAG$ laser because these crystals have larger emission cross-sections.

The relaxation time of the first excited-state in the $Cr^{4+}:YAG$ is in the microsecond region, which prevents mode locking by saturable absorption. Nevertheless, recent investigations [8] show that excited-state absorption (ESA) in $Cr^{4+}:YAG$ is rather significant and the relaxation time from higher-lying levels to the first excited state is in the sub-nanosecond region. This property indicates that there could be a potential to use this excited-state absorption for generation of Q-switched and mode-locked pulses. This possibility has been observed by experiments in which Q-switched mode-locked pulses were generated by use of $Cr^{4+}:YAG$ in a flashlamp-pumped $Nd^{3+}:YAG$ laser with a modulation depth of approximately 30$\sim$70% [9].

Although the large gain cross section of the $Nd^{3+}:YVO_4$ crystal in comparison with that of $Nd^{3+}:YAG$ is unfavorable for obtaining passive Q-switched operation, it is, as is the wider gain bandwidth, favorable for mode-locked operation. Therefore, it is of practical interest to achieve simultaneous mode-locking and Q-switching in the $Nd:YVO_4$–$Cr^{4+}:YAG$ laser for increasing the peak power. In this paper, we present a passively Q-switched and mode-locked diode-pumped $Nd:YVO_4$ laser by use of a $Cr^{4+}:YAG$ crystal as the saturable absorber. Parametric studies of pulsed mode-locking were performed. The experimental configuration and the results for different $Cr^{4+}:YAG$ crystals are described and discussed.

II. Experimental

Fig. 1 outlines the basic laser setup. The pump power is a 20-W fiber-coupled diode-laser array (Coherent, FAP-81-20C-800-B), with the output wavelength of the

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Y. F. Chen is with the Department of Electrophysics, National Chiao Tung University, Hsinchu, Taiwan 30050, R.O.C. (e-mail: yfchen@cc.nctu.edu.tw).

S. W. Tsai is with the Institute of Electro-Optical Engineering, National Chiao Tung University, Hsinchu, Taiwan, R.O.C.

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lasers at 25 °C ranging from 807 to 810 nm. The fibers were drawn into round bundles of 0.8-mm diameter with a numerical aperture of 0.18. A focusing lens with 20-mm focal length and 85% coupling efficiency was used to re-image the pump beam onto the laser crystal. The waist diameter of the pump beam was about 400 μm. The a-cut 0.3-at.% Nd^{3+}, 10-mm-long Nd : YVO_4 crystal was 0.5° wedged and coated for high reflectivity at 1064-nm (R >99.9%) and high transmission at 808-nm (T >95%) on one side. The other side was antireflection coated at 1064 nm. The Nd : YVO_4 crystal of only a low doping concentration was used to avoid thermally induced fracture [10]. The laser crystal was wrapped with indium foil, and mounted in a water-cooled copper block. The water temperature was maintained at 17 °C. The cavity was designed to easily allow mode matching with the pump beam, and to provide the proper spot size in the saturable absorber. Several Cr^{4+} : YAG crystals with different initial transmissions were used in the experiment. Both sides of the Cr^{4+} : YAG crystal were antireflection coated at 1064 nm. The resonator consisted of two spherical highly-reflective (at 1064 nm) mirrors M1 and M2, with radii of curvature of 50 and 10 cm, separated by 60 cm. The flat output coupler was 1.0° wedged. The total cavity length was approximately 1 m. The ratio between the effective area in the gain medium and in the saturable absorber A/A_s can be easily changed by changing the position of the Cr^{4+} : YAG crystal. Moving the Cr^{4+} : YAG crystal away from the output coupler decreases the ratio A/A_s in the present cavity. The experimental result shows that a ratio of greater than 3.0 is sufficient for effective Q-switching. This result is consistent with the theoretical analysis of the following section.

III. Analysis

A. Q-Switching

The physical meaning of the second threshold in a passively Q-switched operation is whether the saturable absorber will saturate first, thereby allowing the photon density to increase and thus producing a giant pulse. Alternatively, the gain will begin to saturate first, so that the photon density never increases sufficiently to develop a giant pulse. To model the operation of a passively Q-switched laser, we shall assume uniform pumping of the gain medium, and the intracavity optical intensities in the gain medium and in the absorber as axially uniform. We also omit the spontaneous emission of the laser and the absorber. The coupled rate equations have been used to model a passively Q-switched laser in many investigations [11]–[14]. Here, we extend the previous results by including the influence of intracavity focusing and the ESA effect. The coupled equations for a three or a four level gain medium are modified as

$$\frac{d\phi}{dt} = \frac{\phi}{t_r}\left[2\sigma n l - 2\sigma_{gs} n_{gs} l_s - 2\sigma_{es} n_{es} l_s - \left(\ln\left(\frac{1}{R}\right) + L\right)\right] \tag{1}$$

$$\frac{dn}{dt} = -\gamma c \sigma \phi n \tag{2}$$

$$\frac{dn_{gs}}{dt} = -\frac{A}{A_s} c \sigma_{gs} \phi n_{gs} \tag{3}$$

$$n_{gs} + n_{es} = n_{so} \tag{4}$$

where

- ϕ intracavity photon density with respect to the effective cross-sectional area of the laser beam in the gain medium;
- n population density of the gain medium;
- l_s length of the saturable absorber;
- A/A_s ratio between the effective area in the gain medium and in the saturable absorber;
- n_{gs} ground-state population density in the saturable absorber;
- n_{es} excited-state population density in the saturable absorber;
- n_{so} total population densitiy in the saturable absorber;
- σ_{gs} GSA cross section in the saturable absorber;
- σ_{es} ESA cross section in the saturable absorber;
- σ stimulated emission cross section of the gain medium;
- l length of the gain medium;
- L nonsaturable intracavity round-trip dissipative optical loss;
- R reflectivity of the output mirror;
- γ inversion reduction factor ($\gamma = 1$ and $\gamma = 2$ correspond to, respectively, four-level and three-level systems (see [11]);

and $t_r = 2l'/c$ is the round-trip transit time of light in the cavity of optical length l', where c is the speed of light.

Dividing (2) by (3) and integrating gives

$$n_{gs} = n_{so}\left(\frac{n}{n_i}\right)^{\alpha} \tag{5}$$

where

$$\alpha \equiv \frac{1}{\gamma}\frac{\sigma_{gs}}{\sigma}\frac{A}{A_s} \tag{6}$$

and n_i is the initial population inversion density in the gain medium. n_i is determined from the condition that the round-trip gain is exactly equal to the round-trip losses just before the Q-switch opens. Thus

$$n_i = \frac{\ln\left(\frac{1}{T_o^2}\right) + \ln\left(\frac{1}{R}\right) + L}{2\sigma l} \tag{7}$$

where $T_o = \exp(-\sigma_{gs} n_{so} l_s)$ is the initial transmission of the saturable absorber. Dividing (1) by (2) and substituting (5) into the result gives

$$\frac{d\phi}{dn} = -\frac{l}{\gamma l'}\left[1 - \frac{(1-\beta)}{2\sigma l n_i}\ln\left(\frac{1}{T_o^2}\right)\left(\frac{n}{n_i}\right)^{\alpha-1} - \frac{\beta\ln\left(\frac{1}{T_o^2}\right) + \ln\left(\frac{1}{R}\right) + L}{2\sigma l n}\right] \tag{8}$$

where

$$\beta = \frac{\sigma_{es}}{\sigma_{gs}}. \tag{9}$$

Since the first derivative of ϕ with respect to n at $n = n_i$ is zero, the criterion for achieving Q-switching is whether the second derivative of ϕ with respect to n at $n = n_i$ has a positive or a negative sign. If positive, the photon density will grow. Using (8), the second derivative of ϕ with respect to n is given by

$$\frac{d^2\phi}{dn^2} = -\frac{l}{\gamma l'}\left[-\frac{(1-\beta)(\alpha-1)}{2\sigma l n_i^2}\ln\left(\frac{1}{T_o^2}\right)\left(\frac{n}{n_i}\right)^{\alpha-2} + \frac{\beta\ln\left(\frac{1}{T_o^2}\right)+\ln\left(\frac{1}{R}\right)+L}{2\sigma l n^2}\right]. \quad (10)$$

Setting $n = n_i$ in (10), the criterion for a giant pulse to occur is then given by

$$[\alpha(1-\beta)-1]\ln\left(\frac{1}{T_o^2}\right) - \ln\left(\frac{1}{R}\right) - L > 0. \quad (11)$$

Inserting (6) into (11), the criterion for the second threshold becomes

$$\frac{\ln\left(\frac{1}{T_o^2}\right)}{\ln\left(\frac{1}{T_o^2}\right)+\ln\left(\frac{1}{R}\right)+L}\frac{\sigma_{gs}}{\sigma}\frac{A}{A_s} > \frac{\gamma}{1-\beta}. \quad (12)$$

The main difference between the present derivation and the previous result [5] is that we take account of the influence of excited-state absorption and intracavity focusing. In addition, (12) is of practical importance because the parameters used in the present derivation, such as T_o and R, are directly related to the design of a passively *Q*-switched laser. For the $Cr^{4+}:YAG$ passively *Q*-switched $Nd:YVO_4$ laser, $\gamma = 1$, $\beta \approx 0.28$ [8], $\sigma_{gs} = 70 \times 10^{-19}$ cm^2 [8], and the emission cross section of $Nd:YVO_4$, σ, is 25×10^{-19} cm^2 [15].

Following the derivation of previous work [11]–[13], the pulse energy is given by

$$E = \frac{h\nu A}{2\sigma\gamma}\ln\left(\frac{1}{R}\right)x \quad (13)$$

where x is the solution of the equation

$$1-\exp(-x) - \frac{(1-\beta)\ln\left(\frac{1}{T_o^2}\right)}{\ln\left(\frac{1}{T_o^2}\right)+\ln\left(\frac{1}{R}\right)+L}\frac{1-\exp(-\alpha x)}{\alpha} - \frac{\beta\ln\left(\frac{1}{T_o^2}\right)+\ln\left(\frac{1}{R}\right)+L}{\ln\left(\frac{1}{T_o^2}\right)+\ln\left(\frac{1}{R}\right)+L}x = 0. \quad (14)$$

To consider the dependence of the output energy on A/A_s, we used (13) and (14) to calculate the output pulse energy in a $Cr^{4+}:YAG$ passively *Q*-switched $Nd:YVO_4$ laser as a function of $A/A_s$for several initial transmissions T_o and $R = 0.55$. Fig. 2 shows the calculation results. It can be seen that the output pulse energy initially rises as the ratio A/A_s is increased above the second threshold. As the ratio A/A_s is sufficiently large, the output energy saturates at a larger value for a smaller T_o. To obtain a nearly optimum output pulse energy, the ratio A/A_s was designed to be greater than 3.0 in the passively *Q*-switched $Nd^{3+}:YVO_4$–$Cr^{4+}:YAG$ laser.

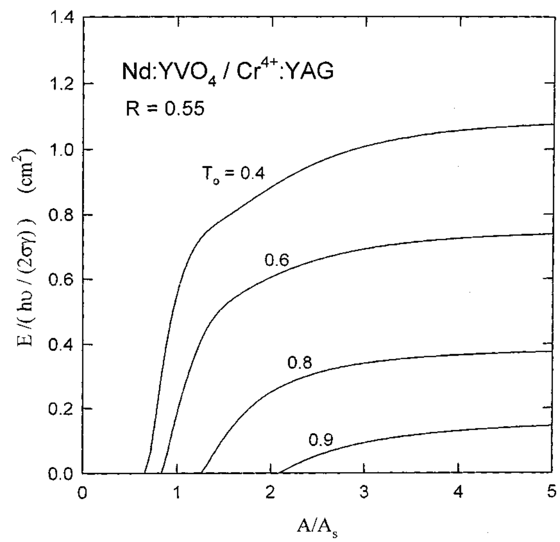

Fig. 2. Calculation results for the output pulse energy in the passively *Q*-switched $Nd:YVO_4$–$Cr^{4+}:YAG$ laser as a function of $A/A_s$for several initial transmissions T_o and $R = 0.55$.

B. Mode-Locking

The nonlinear absorption of saturable absorbers was first successfully employed for simultaneous *Q*-switching and mode-locking of solid-state lasers in 1965 [16], [17]. One desirable condition for good pulsed mode-locking is that the saturable absorber should have a short enough lifetime to recover its absorption between individual noise bursts, so that the preferred pulse does not bring several closely following noise spikes up along with it. Another important condition is that the build-up time of the *Q*-switched pulse has to be sufficiently short because of the limited round trip time of the intensity fluctuation. In early technologies, dyes were commonly employed in pulsed mode-locked solid-state lasers. However, a flowing dye solution temperature controlled within ±0.1 °C must be used to achieve stable and reproducible performance because a change of 1% per degree in absorption was found in the diluted dyes. Furthermore, mixing with handling of the dye solution, and maintaining proper dye concentration, proved cumbersome. Due to these inherent shortcomings, the replacement of the dyes by a solid-state element is desirable.

In comparison with dye solution, $Cr^{4+}:YAG$ has better thermal and mechanical properties, resulting in a higher damage threshold. However, its relaxation time is in the microsecond region, which generally would not be allowed to obtain mode locking. Semiconductor saturable absorber mirrors or Kerr-lensed mode-locked systems are commonly used technologies in pulsed solid-state lasers [18], [19]. Nevertheless, when the intracavity intensity is high enough, all of the Cr^{4+} ions are quickly excited to the first excited-state, and strong ESA causes a great quantity of Cr^{4+} ions to accumulate in higher-lying levels. Since the relaxation time of the ESA is relatively short (τ_{es} ≈0.1 ns) [20], passive mode-locking with a $Cr^{4+}:YAG$ saturable absorber would be possible if strong intensity fluctuations are introduced, and the pulse buildup time is sufficiently short [21].

The fluctuation mechanism is believed to be mainly responsible for generating ultrashort pulses in a laser Q-switched by nonlinear absorbers [21], [22]. According to this mechanism, the picture of ultrashort pulse formation is the following. In the linear stage of generation, the fluctuations of intensity arise due to the interference of a great number of modes having a random phase distribution so that the radiation consists of a chaotic collection of ultrashort peaks. In the nonlinear stage, where bleaching of the absorber takes place, the most intensive fluctuation peaks are compressed and amplified faster than all the weaker ones. Kryukov and Letokhov [22] used the fluctuation mechanism to prove that the ratio of the peak pulse power to the mean background power can be given by

$$\frac{P_m}{P_{\text{backgr}}} \cong (\ln m)^{\mu} \tag{15}$$

where m is the number of axial modes at the end of the linear stage of buildup and μ is the nonlinear parameter related to the pulse compression in the nonlinear stage of the developing. To obtain the high pulse-to-background ratio, m and μ should be as large as possible.

During the linear stage of the intensity fluctuation buildup, the number of axial modes decreases due to the natural selection toward the center of amplification line given by [22]

$$m = \frac{m_o}{(\alpha_o(t_b/t_r))^{1/2}} \tag{16}$$

where

m_o initial number of axial modes;
α_o threshold gain;
t_b pulse build-up time.

In most cases, the nonlinear parameter is given by [22] as

$$\mu = \frac{1 - T_o}{t_b(\mathrm{d}\alpha/\mathrm{d}t)} \tag{17}$$

where $\mathrm{d}\alpha/\mathrm{d}t$ is the speed of the gain increase due to pumping at the time of threshold. From (15)–(17) it can be found that a shorter pulse build-up time generally leads to a larger m and a larger μ, and a higher pulse-to-background ratio.

Since a short pulse build-up time is of benefit to the generation of the Q-switched and mode-locked pulses, it is practically useful to make an estimate of the build-up time for a simple situation. The Q-switch build-up time in a laser can be estimated from a solution of the single mode rate equations. The addition of simultaneous mode locking and the presence of multimode oscillations will not significantly change the build-up time [23], [24]. If the pulse build-up time t_b is short compared to the upper-level lifetime of the inversion density, then a good estimate for t_b is given by [5]

$$t_b = (25 \pm 5)t_r C_b \tag{18}$$

with

$$C_b = \frac{n_{th}}{n_i - n_{th}} \frac{1}{\ln(1/R)} \tag{19}$$

where n_{th} is the threshold inversion density after the absorber is bleached. The absorber is assumed to be fully bleached in the analysis. Note that full bleaching is not a necessary condition for obtaining Q-switching. Owing to the excited-state absorption, the final transmission of the saturable absorber will be

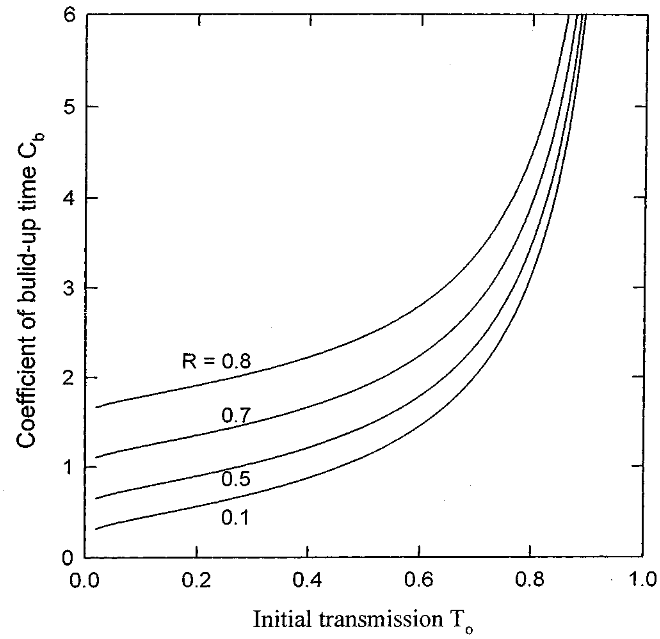

Fig. 3. Dependence of the coefficient of pulse-build time on T_o for several values of front mirror reflectivity R for Cr^{4+} : YAG ($\beta = 0.28$).

$T_f = \exp(-\sigma_{es} n_{so} l_s) = T_o^{\beta}$, where the factor β is defined in (9). Therefore, the threshold inversion density after bleaching of the absorber is given by

$$n_{th} = \frac{\beta \ln\left(\frac{1}{T_o^2}\right) + \ln\left(\frac{1}{R}\right) + L}{2\sigma l}. \tag{20}$$

The difference between (7) and (20) arises from the different losses incurred by the absorber without any bleaching and with complete bleaching.

Substituting (7) and (20) into (19), the pulse build-up time coefficient is rewritten as

$$C_b = \frac{\beta \ln\left(\frac{1}{T_o^2}\right) + \ln\left(\frac{1}{R}\right) + L}{(1-\beta)\ln\left(\frac{1}{T_o^2}\right)} \frac{1}{\ln\left(\frac{1}{R}\right)}. \tag{21}$$

Fig. 3 provides a demonstration of the dependence of C_b on T_o for several values of R for Cr^{4+} : YAG ($\beta = 0.25$) . For the demonstration, we used a typical value of $L = 0.003$ in the calculation. It can be seen that the lower the initial transmission, the shorter is the build-up time for a given output reflectivity. On the other hand, the build-up time can be clearly reduced by lowering the output reflectivity for a given initial transmission. However, a lower output mirror reflectivity also results in a higher threshold. Therefore, the output reflectivity is typically chosen to range between 50%–60% for pulsed passive mode-locking [25].

IV. Results and Discussion

Initially, we used an output coupler with $R = 55\%$ to generate simultaneous Q-switching and mode locking. Fig. 4 shows the average power of the passively Q-switched and mode-locked pulse train with respect to the pump power for saturable

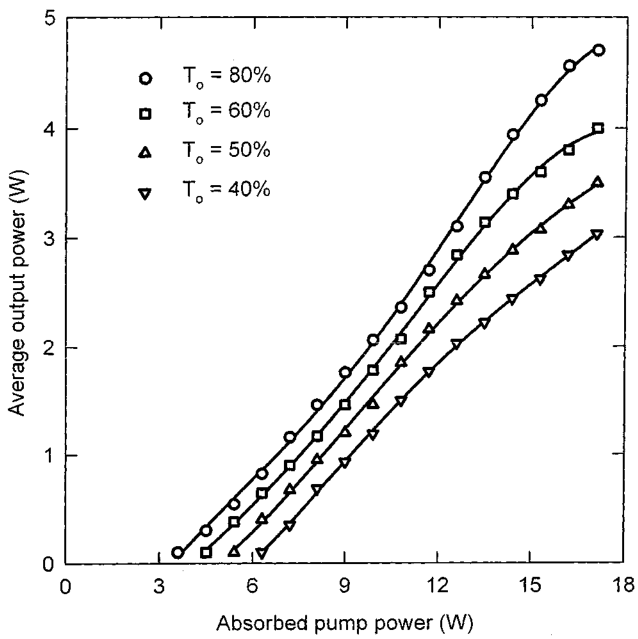

Fig. 4. Experimental results for average power of the passively Q-switched mode-locked pulse train with respect to the pump power for saturable absorbers of T_o =80%, 60%, 50%, and 40%, respectively.

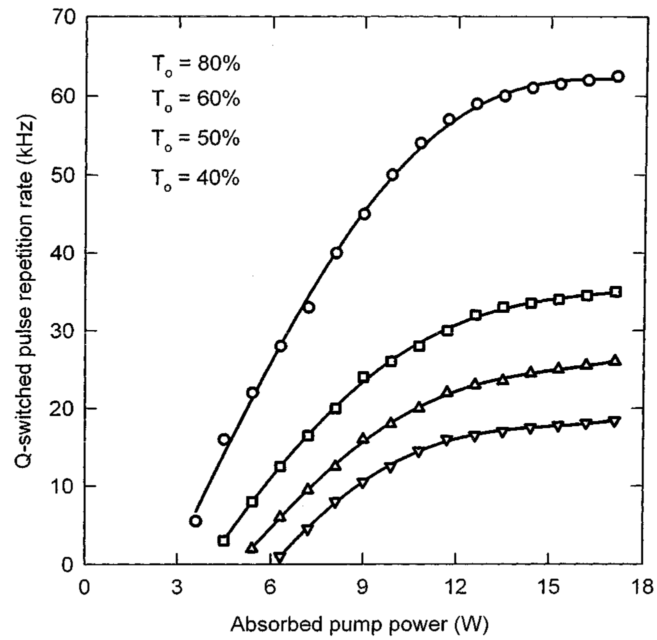

Fig. 5. Experimental results for pulse repetition rate of the Q-switched pulse train with respect to the pump power for saturable absorbers of T_o =80%, 60%, 50%, and 40%, respectively.

absorbers of T_o= 80%, 60%, 50%, and 40%, respectively. The highest average output power is obtained with a T_o =80% Cr^{4+} : YAG crystal and the Nd : YVO_4 laser generates an average output power 4.7 W in the TEM_{00} mode at an incident pump power of 17-W. The lasing threshold and optical slope efficiency are 3.2 W and 34.5%, respectively. For a Cr^{4+} : YAG crystal of initial transmissions of 60%, 50%, and 40%, the maximum average output powers are reduced to 4, 3.5, and 3.0 W, respectively, because of the increasing losses incurred by the saturable absorbers. The lasing threshold and the slope efficiency are 4.3 W and 31.5% for the T_o= 60% crystal, 5.1 W and 29.4% for the T_o= 50% crystal, and 6.0 W and 27.3% for the T_o =40% crystal, respectively.

The pulse temporal behavior was recorded by a LeCroy 9362 digital oscilloscope (500-MHz bandwidth) and a fast Si p-i-n photodiode with a rise time of 0.35 ns. Fig. 5 shows the repetition rate of the Q-switched pulse train with respect to the pump power for the four Cr^{4+} : YAG crystals and R= 55%. It can be seen that the lower the initial transmission of the Cr^{4+} : YAG crystal, the lower is the repetition rate of the Q-switched pulse train. From Figs. 4 and 5, the pulse energies of the Q-switched pulse train at an incident pump power of 17 W are 75, 120, 140, and 165 μJ for saturable absorbers of T_o= 80%, 60%, 50%, and 40%, respectively. A typical oscilloscope trace is presented in Fig. 6, showing a train of Q-switched pulses. The pulse-to-pulse amplitude fluctuation of the Q-switched pulse train was found to be less than ±10%.

The expanded temporal shape of a single Q-switched pulse for saturable absorbers of T_o= 80%, 60%, and 40% is shown in Fig. 7. It can be seen that a lower T_o not only shortens the width of the pulse envelope, but also reduces the CW background in the Q-switched and mode-locked pulse. This result is consistent

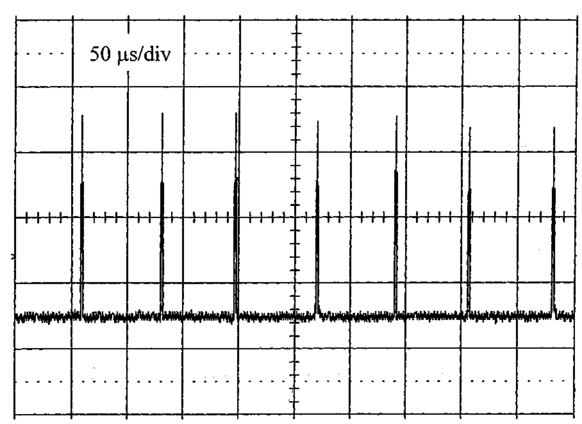

Fig. 6. Oscilloscope traces of a train of Q-switched pulses.

with the previous analysis that a lower T_o shortens the pulse build-up time, as shown in Fig. 3, which is beneficial for the generation of the Q-switched and mode-locked pulses. The pulse build-up times were estimated to be about 590, 320, and 200 ns for saturable absorbers of T_o= 80%, 60%, and 40%, respectively. On the other hand, the theoretical results shown in Fig. 3 are 560, 297, and 198 ns for saturable absorbers of T_o= 80%, 60%, and 40%, respectively. Apparently, the theoretical calculations are in good agreement with the experimental results. When the value of T_o in our system is smaller than 0.6, nearly complete mode locking with more than 90% of the output power mode-locked is achieved. Although the results shown in Fig. 7 were measured at 10 W of absorbed pump power, the envelope pulse-width changes by less than ±5% over the range of the absorbed pump power (8∼17 W). The mode-locked pulses inside the

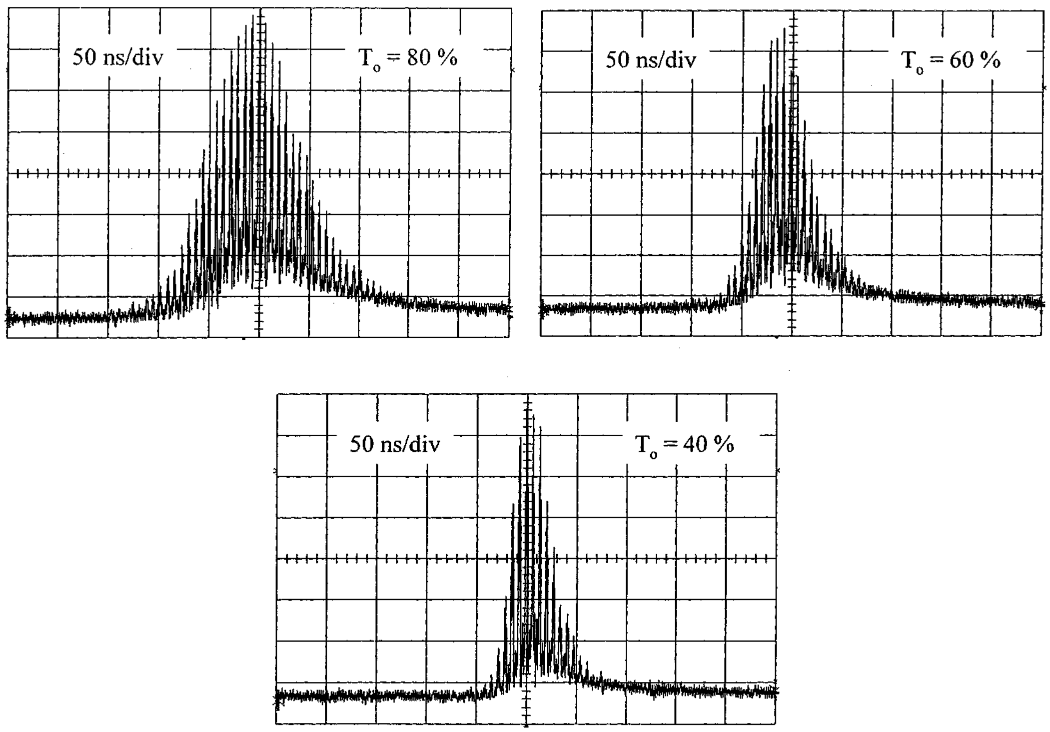

Fig. 7. Expanded temporal shape of a single *Q*-switched pulse for saturable absorbers of T_o= 80%, 60%, and 40% with R =55% at the pump power of 10 W.

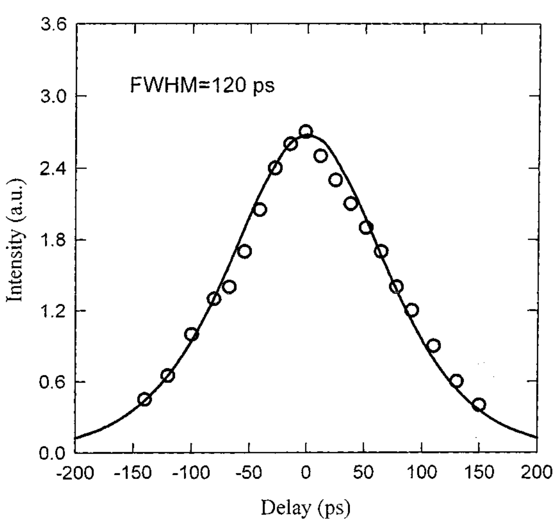

Fig. 8. Autocorrelation trace of the *Q*-switched mode-locked pulse.

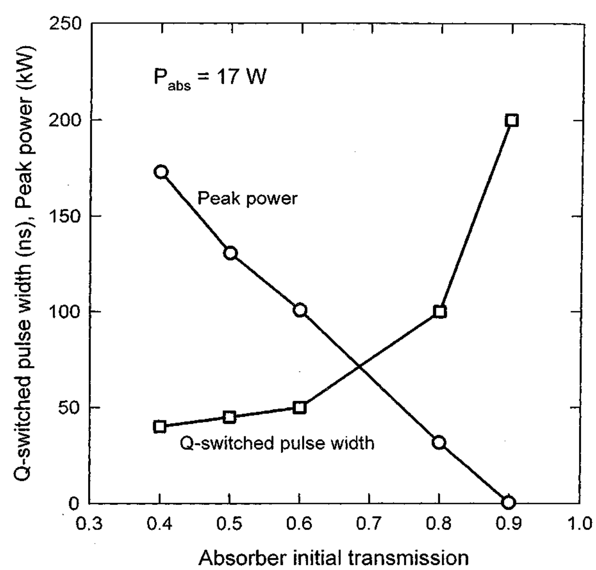

Fig. 9. Dependence of the envelope pulse width and the peak power of the *Q*-switched pulse train on the initial transmission at an incident pump power of 17-W.

Q-switched pulse envelope had a repetition rate of ~148 MHz. The mode-locked pulse duration inside the *Q*-switched pulse was measured using an autocorrelator (KTP type II interaction) in a collinear configuration [26]. The average pulse duration (FWHM) was estimated to be about 110~150 ps for $T_o \leq 0.6$, as shown in Fig. 8. Fig. 9 shows the dependence of the envelope pulse width and the peak power of the *Q*-switched pulse train on the initial transmission at an incident pump power of 17 W. The peak power of a single pulse near the maximum of the *Q*-switched envelope was greater than 100 kW for $T_o \leq 0.6$.

To investigate the stability of the mode-locking process, we changed the spot size in the absorber by moving the absorber away from the output coupler. It was found that increasing the spot size in the absorber leads to a decrease in the pulse energy of the whole bunch. However, the modulation depth of the mode-locking pulse train is almost not influenced by the change

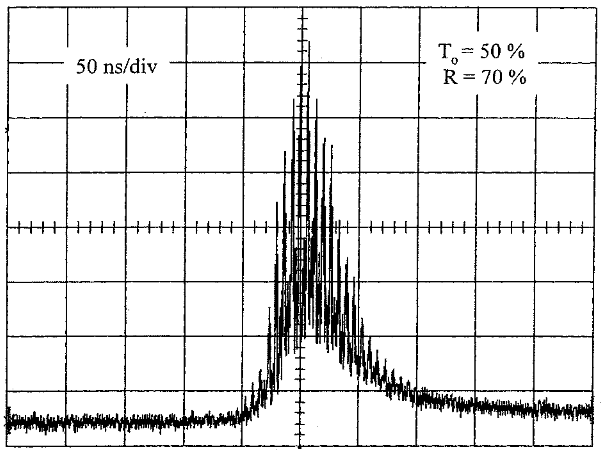

Fig. 10. Expanded temporal shape of a single Q-switched pulse for $T_o = 50\%$ and $R = 70\%$ at a pump power of 10 W.

of the beam size in the absorber. It has also been found that mode-locking operation is insensitive to the alignment of the absorber. Therefore, the key parameter for mode-locking is the initial absorber transmission, whereas tight focusing only affected passively Q-switching operation.

Finally, we replaced the output coupler ($R = 55\%$) with a $R = 70\%$ one to study the influence of the output reflectivity on the modulation depth of the mode-locked pulse. In this case, the modulation depth of the mode-locked pulse decreased significantly, as shown in Fig. 10. The reason is that a higher output reflectivity will lengthen the pulse-build up time, as anticipated by Fig. 2.

V. Conclusions

We have demonstrated the use of Cr^{4+} : YAG crystal to obtain a high-power diode-pumped Nd : YVO_4 laser operating in a Q-switched mode-locked mode. Theoretical analysis shows that a lower initial transmission of Cr^{4+} : YAG crystal is of benefit to the generation of the Q-switched mode-locked pulses for a given output reflectivity. On the other hand, the value of the output reflectivity should be low enough for simultaneous mode-locking and Q-switching. Experimental results show that over 90% of the output power in a passively Q-switched Nd : YVO_4 laser was mode-locked by using $T_o \leq 60\%$ and $R = 55\%$. The peak power of a single pulse near the maximum of Q-switched envelope was greater than 100 kW. We believe that its high reliability and stability make this laser of considerable interest for applications.

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