High-power diode-pumped Q-switched and mode-locked Nd:YVO_4 laser with a Cr^{4+}:YAG saturable absorber

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We demonstrate a high-power passively Q-switched and mode-locked Nd:YVO_4 laser with a Cr^{4+}:YAG saturable absorber. 2.7 W of average power with an 18-kHz Q-switched repetition rate was generated at a 12.5-W pump power. The peak power of a single pulse near the maximum of the Q-switched envelope was greater than 100 kW.

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Chromium-doped yttrium aluminum garnet (Cr^{4+}:YAG) provides a large absorption cross section in the spectral region 0.9–1.2 μm, which makes it attractive for passive Q switching of Nd-doped lasers.[1,2] In comparison with other Q-switching materials, such as dye solutions, Cr^{4+}:YAG has better thermal and mechanical properties, resulting in a higher damage threshold. On the other hand, its relaxation time is in the microsecond region, which prevents mode locking as a general saturable absorber. However, recent investigations[3] showed that the excited-state absorption (ESA) in Cr^{4+}:YAG is rather significant and that the relaxation time from higher-lying levels to the first excited state is in the subnanosecond region. There could be potential to use this ESA for generation of Q-switched mode-locked pulses. This possibility was observed in an experiment in which Q-switched mode-locked pulses were generated by use of Cr^{4+}:YAG inside a flash-lamp-pumped Nd:YAG laser with a modulation depth of approximately 30% to 70%.[4] In this Letter we present a passively Q-switched and mode-locked diode-pumped neodymium-doped yttrium vanadate (Nd:YVO_4) laser with a Cr^{4+}:YAG crystal as the saturable absorber. The criterion for complete mode locking was also investigated.

It is 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:YVO_4 crystal will have a large gain, owing to the high stimulated-emission cross section. For good passive Q switching the saturation in the absorber must occur before the 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. From analysis of the coupled rate equation, the criterion for good passively Q-switching is given by[6]

$$\frac{\ln(1/T_0{}^2)}{\ln(1/T_0{}^2) + \ln(1/R) + L}\,\frac{\sigma_{\mathrm{gs}}}{\sigma}\,\frac{A}{A_s} > \frac{\gamma}{1-\beta}\,, \qquad (1)$$

where T_0 is the initial transmission of the saturable absorber, A/A_s is the ratio of the effective area in the gain medium and in the saturable absorber, R is the reflectivity of the output mirror, L is the nonsaturable intracavity round-trip dissipative optical loss, σ_{gs} is the ground-state absorption cross section of the saturable absorber, σ is the stimulated-emission cross section of the gain medium, γ is the inversion reduction factor ($\gamma = 1$ and $\gamma = 2$ correspond to four-level and three-level systems), and β is the ratio of the ESA cross section to that of the ground-state absorption in the saturable absorber. Although the large gain cross section of the Nd:YVO_4 crystal in comparison with that of Nd:YAG is unfavorable for obtaining passive Q-switched operation, it is, as is the wider gain bandwidth, favorable for mode-locked operation.

When the intracavity intensity of the laser is low, most of the population is in the ground state, and the transition of the ESA in the Cr^{4+}:YAG crystal to higher-lying levels is rather weak. In this case, Cr^{4+}:YAG crystal is an effective saturable absorber only for Q switching. However, when the intracavity intensity is high enough, all Cr^{4+} ions are quickly excited to the first excited state, and the strong ESA causes a great quantity of Cr^{4+} ions to accumulate in higher-lying levels, which leads to saturation of the ESA. Since the relaxation time of the ESA is relatively short ($\tau_{\mathrm{es}} \approx 0.1$ ns),[7] passive mode locking with a Cr^{4+}:YAG saturable absorber would be possible if the intracavity intensity were strong enough to make ESA saturable. The saturable intensity for the ESA is given by $I_s = h\nu/\sigma_{\mathrm{es}}\tau_{\mathrm{es}}$, where $h\nu$ is the laser photon energy and σ_{es} is the ESA cross section. The published values for σ_{es} are in the range $2.2\text{–}8 \times 10^{-19}$ cm^2.[8–10] With these values we obtained $I_s = 2.4\text{–}8.6$ $\mathrm{GW/cm}^2$. In other words, the intracavity intensity must reach the order of gigawatts per square centimeter if one is to achieve good passive mode locking with a Cr^{4+}:YAG crystal.

Theoretically, the light intensity in the saturable absorber is proportional to initial population density n_i

in the gain medium. The initial population density is determined from the condition that the round-trip gain be exactly equal to the round-trip losses just before the Q switch opens; i.e.,[6]

$$n_i = \frac{\ln(1/T_0{}^2) + \ln(1/R) + L}{2\sigma l}. \qquad (2)$$

Since Nd:YVO$_4$ crystal has a large gain cross section, the value of the initial absorber transmission (parameter T_0) must be low enough to yield a large initial population density.

Figure 1 shows the basic outline of the laser setup: The pump power is provided by a 16-W fiber-coupled diode-laser array (Coherent FAP-81-16C-800-B) with the output wavelength of the lasers at 25 °C ranging from 807 to 810 nm. The fibers were drawn into round bundles with a 0.8-mm diameter and a numerical aperture of 0.18. A focusing lens with 20-mm focal length and 85% coupling efficiency was used to reimage the pump beam into the laser crystal. The waist diameter of the pump beam was ~400 μm. The a-cut, 0.3-at.%, 10-mm-long Nd:YVO$_4$ crystal was 0.5° wedged and coated for highly reflectivity at 1064 nm ($R > 99.9\%$) and high transmission at 808 nm ($T > 95\%$) on one side, and the other side was antireflection coated at 1064 nm. A Nd:YVO$_4$ crystal with low doping concentration was used to prevent thermally induced fracture. The laser crystal was wrapped with indium foil and mounted in a water-cooled copper block. The water temperature was maintained at 17 °C. We designed the cavity to easily allow mode matching with the pump beam and to provide the proper spot size in the saturable absorber. The resonator consisted of two spherical highly reflective (at 1064 nm) mirrors, M1 and M2, with radii of curvature of 50 and 10 cm, respectively, separated by 60 cm. The flat output coupler was 1.0° wedged. The total cavity length was ~1 m. The ratio A/A_s in the present cavity was approximately 20–30.

The pulse's 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. Various Cr^{4+}:YAG crystals with different initial transmission and various output couplers with different reflectivity were used to optimize the output performance. The oscilloscope traces presented in Fig. 2 show that a lower T_0 not only shortens the width of the pulse envelope but also enhances the modulation depth. The experimental results show that, when the value of T_0 in our system is smaller than 0.6, the laser can operate in the Q-switched mode-locked state. Nearly complete mode locking with more than 90% of the output power mode locked is achieved. The mode-locked pulse duration inside the Q-switched pulse was measured with an autocorrelator (KTP type II interaction) in collinear configuration. The average pulse duration (FWHM) was estimated to be ~106 ps. Although the results shown in Fig. 2 were measured at 10 W of absorbed pump power, the envelope pulse length changed within ±5% over the 8–13-W range of the absorbed pump power. The mode-locked pulses inside the Q-switched pulse envelope had a repetition rate of ~148 MHz.

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 of the pulse energy of the whole Q-switched pulse. However, the modulation depth of the mode-locking pulse train is only slightly influenced by the change of the beam size in the absorber. It was also found that the mode-locking operation is insensitive to the alignment of the absorber. Therefore the key parameter for the mode-locking process is the

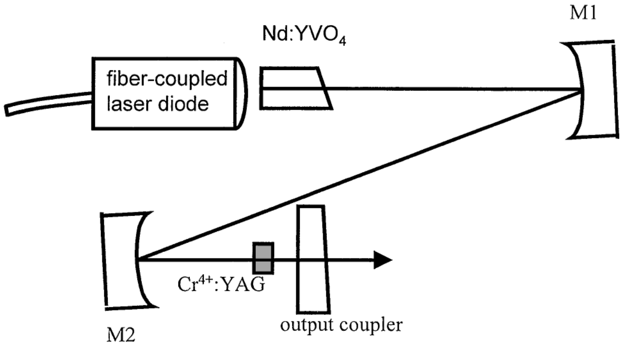

Fig. 1. Configuration of a passively Q-switched and mode-locked Nd:YVO$_4$ laser.

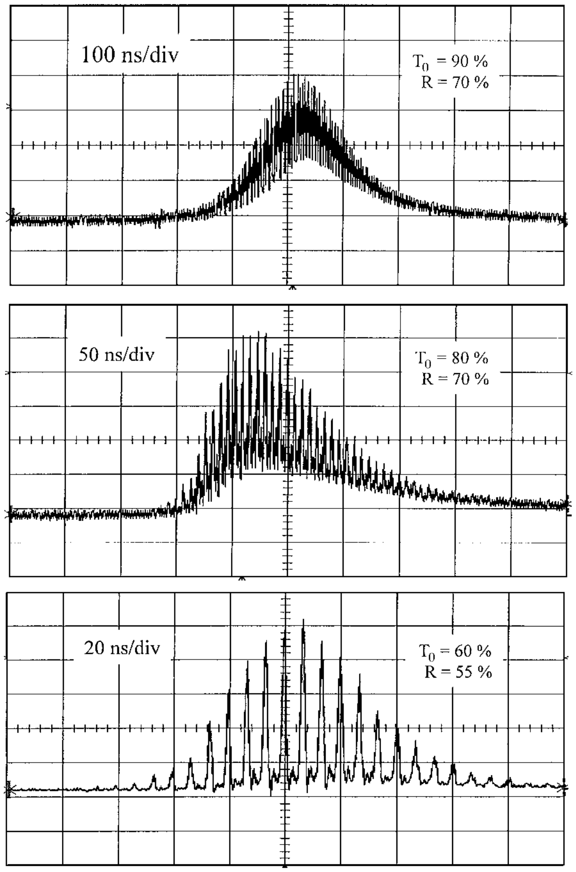

Fig. 2. Oscilloscope traces of a Q-switched and mode-locked laser pulse.

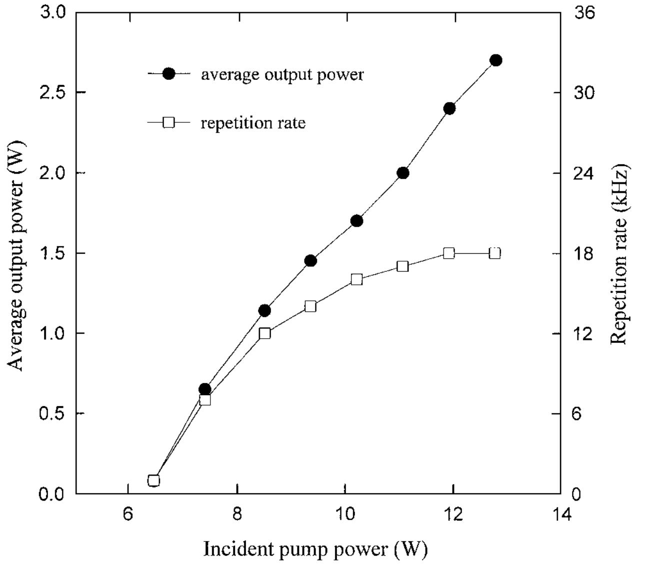

Fig. 3. Dependence of the average output power and pulse repetition rate of the Q-switched pulse train on the absorbed pump power.

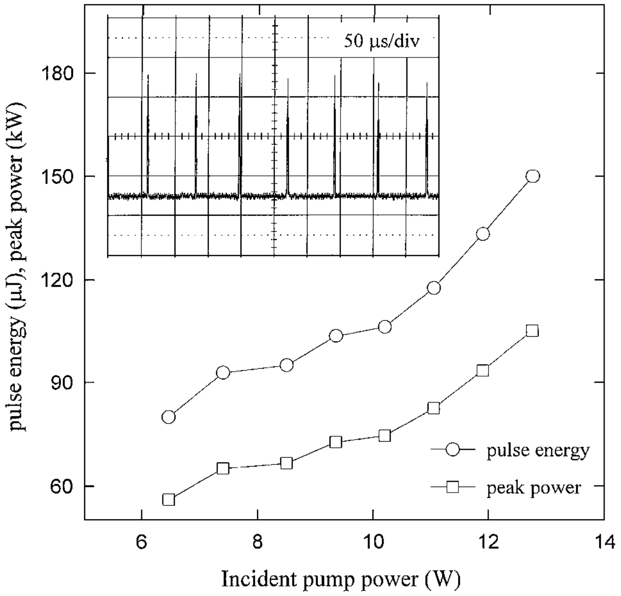

Fig. 4. Dependence of the pulse energy and peak power of the Q-switched pulse train on the absorbed pump power. An oscilloscope trace of a train of Q-switched pulses is shown in the inset.

initial absorber transmission, whereas tight focusing affected only passive Q-switching operation. We believe that this laser's high reliability and stability make it of considerable interest for applications.

Figure 3 shows the average power and the repetition rate of the Q-switched pulse train with respect to the pump power for $T_0 = 60\%$ and $R = 55\%$. The average output power reached 2.7 W, and the repetition rate of the Q-switched pulse was ~18 kHz at 1.25 W of absorbed pump power. The threshold power and the slope efficiency were 6.3 W and 42%, respectively. The output laser was a linearly polarized, nearly diffraction-limited beam ($M^2 \approx 1.3$). Experimental results show that the intracavity intensity damaged the coating of Cr^{4+}:YAG crystal once the pump power was higher than 13 W in the case of $T_0 = 60\%$ and $R = 55\%$. From the output pulse energy, the coating damage threshold of our Cr^{4+}:YAG crystal is estimated to be ~5 GW/cm^2. On the other hand, we found that the present system can operate with good mode-locked output when the intracavity intensity in Cr^{4+}:YAG crystal is larger than ~2 GW/cm^2. Therefore there is a reasonable margin for the coating to survive in normal operating conditions.

Figure 4 shows the dependence of the pulse energy and the peak power of the Q-switched pulse train on the absorbed pump power for $T_0 = 60\%$ and $R = 55\%$. The peak power of a single pulse near the maximum of the Q-switched envelope was greater than 100 kW at 12.5 W of absorbed pump power. The increase of the output pulse energy with the pump power is due to the fact the thermal-lensing effect causes A/A_s to be an increasing function of pump power. Figure 4 also shows the oscilloscope traces of 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%.

We have demonstrated the use of Cr^{4+}:YAG crystal to obtain a high-power diode-pumped Nd:YVO$_4$ laser in Q-switched and mode-locked mode. Over 90% of the output power was mode locked when $T_0 = 60\%$ and $R = 55\%$. 2.7 W of average power with an 18-kHz Q-switched repetition rate was generated at 12.5-W pump power. The peak power of a single pulse near the maximum of the Q-switched envelope was greater than 100 kW.

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