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A diode-pumped high power Q-switched and self-mode-locked Nd:YVO_4 laser with a LiF:F_2^- saturable absorber

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Abstract. Simultaneous mode-locking and Q-switching has been accomplished in a diode-pumped Nd:YVO_4/LiF:F_2^- laser. At an absorbed pump power of 23.6 W, the average output power was 6.0 W and the repetition rate of the Q-switched pulse was 260 kHz. A depth of mode-locking of 100% was obtained and there was no satellite pulse between mode-locked pulse trains. The mode-locked pulse inside the Q-switched pulse had a repetition rate of approximately 148 MHz and its average duration was estimated to be around 75 ps.

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Simultaneous Q-switching and mode-locking is of great interest for the generation of high peak power and ultrashort pulses. The high peak power from a simultaneously Q-switched and mode-locked laser is beneficial to wavelength conversion in an external non-linear crystal [1]. Moreover, the pulse trains contained in Q-switched and mode-locked lasers can be used advantageously to study dynamic optical non-linearities in the 10–1000 ns time interval [2]. The non-linear absorption of saturable absorbers was first successfully employed for the simultaneous Q-switching and mode-locking of solid-state lasers in 1965 [3, 4]. Unlike CW mode-locking, to generate a Q-switched and mode-locked pulse, the intensity fluctuation has to be sufficiently strong and the build-up time of the Q-switched pulses 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. Recently, the generation of passively Q-switched and mode-locked pulses has been performed in diode-pumped solid-state lasers having a Cr^{4+}:YAG saturable absorber [5, 6].

LiF:F_2^- crystal is another well-known absorber for Nd-doped lasers. LiF:F_2^- crystal has a rather high absorption cross section of approximately $2\times10^{-17}\,\mathrm{cm}^2$ in the neighborhood of the Nd-doped laser wavelengths. Furthermore, the LiF crystal has a relatively high thermal conductivity ($0.14\,\mathrm{W\,cm^{-1}\,K^{-1}}$) and the refractive index has a weak temperature dependence ($\mathrm{d}n/\mathrm{d}T = -1.2\times10^{-5}\,\mathrm{K^{-1}}$). Such a device has already been used for passive mode-locking of flash-lamp-pumped Nd:YAG and Nd:glass lasers [7–9] and for passive Q-switching of a diode-pumped Nd:YAG laser [10]. In this letter, we present experimental results for the simultaneous Q-switching and mode-locking of a diode-pumped Nd:YVO_4 laser having a LiF:F_2^- crystal as a saturable absorber.

1 Experimental procedure

Figure 1 outlines the basic laser set-up. The pump was a 25-W fiber-coupled diode-laser array (Coherent FAP-81-25C-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 of 0.8 mm diameter with a numerical aperture of 0.18. A focusing lens with 20 mm focal length and 95% 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+}, 9-mm-long Nd:YVO_4 crystal was 0.5° wedged and coated for antireflection at 1064 nm ($R < 0.2\%$) on both end surfaces. A Nd:YVO_4 crystal having a low dopant concentration was used to avoid thermally induced fracture [11]. The laser crystal was wrapped

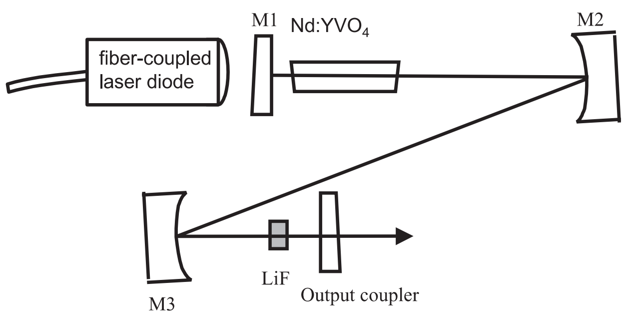

Fig. 1. Configuration of the passively Q-switched mode-locked Nd:YVO_4 laser with a LiF:F_2^- absorber

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with indium foil and mounted in a water-cooled copper block. The water temperature was maintained at 20 °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. The resonator consisted of three highly reflective (at 1064 nm) mirrors M1, M2 and M3, and one output coupler ($R = 70\%$ at 1064 nm). Mirror M1 is the flat mirror; the radii of curvature for M2 and M3 are 50 cm and 10 cm, respectively. M2 and M3 were separated by 60 cm. The flat output coupler was 1.0° wedged. The total cavity length was approximately 1 m.

The LiF:F_2^- saturable absorber was prepared by irradiating pure LiF crystals at room temperature with gamma rays from a MCi (megacurie) cobalt 60 source. From the spectrophotometric traces, there was a transmittance saturation in the F_2^- color centers at 1060 nm when the irradiation dosage exceeded 100 MR. Experimental results showed that overdosage increased the optical density in the visible range only. Before overdosage, the population of the F_2^- color centers was proportional to the irradiation dosage from the cobalt source. The total dosage in the present LiF crystal was about 50 MR. The irradiated crystals were cut and cleaved to the proper size and then polished to give good optical quality, using ordinary optical shop instruments. The non-saturable losses of the LiF:F_2^- crystal were measured to be about 4%. Since the absorption cross section of the LiF:F_2^- crystal is much higher than the emission cross section of the Nd:YVO_4 crystal, tight focusing in the absorber was not necessary [12]. Therefore, the absorber was placed 1 cm away from the output coupler to give the optimum performance.

2 Results and discussion

Two LiF:F_2^- crystals were used in the present experiment. Sample 1 had a low-signal transmission $T_0 \approx 90\%$, and was 1.8 mm long, whereas sample 2 had $T_0 \approx 83\%$ and was 4 mm long. Figure 2 shows the average output power with respect to the absorbed pump power for sample 1. It can be seen that the lasing threshold and optical slope efficiency were 4.0 W and 30.6%, respectively. At an absorbed pump power of 23.6 W, the average output power was 6.0 W and the repetition rate of the Q-switched pulse was 260 kHz. Experimental results indicate that the unsaturated loss of the LiF:F_2^- absorber is rather low. The pulse temporal behavior was recorded using a LeCroy 9362 (500 MHz bandwidth) and a high speed InGaAs photodiode with a rise time of approximately 0.1 ns. A typical oscilloscope trace for the sample 1 is presented in Fig. 3, showing a train of Q-switched pulses. Without proper alignment, the Q-switched pulse showed intensity and timing jitter, which at worst was of the order of 40%. With proper alignment the timing jitter and the peak-to-peak amplitude fluctuation of the Q-switched envelope could be reduced to ±10% at 5 ∼ 15 W absorbed pump power. We noticed that the Q-switched pulse trains tended to bifurcate and produce alternating strong and weak pulses when the pump power was greater than 15 W, i.e. at a pulse repetition rate higher than 160 kHz. Typically, the Q-switched pulse envelope had a temporal duration of approximately 250 ns and the mode-locked pulses inside the Q-switched pulse had a repetition rate of ∼ 148 MHz, as shown in Fig. 4a and b. It can be seen that a 100% depth of mode-locking was achieved

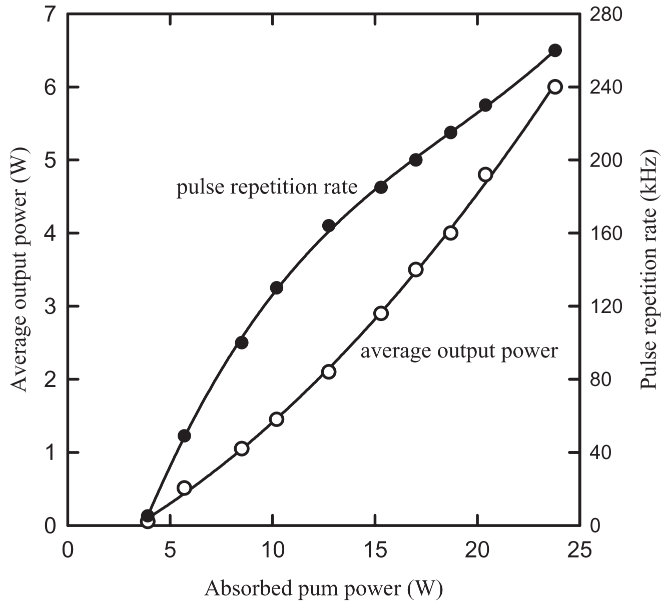

Fig. 2. Average output power and repetition rates of the passively Q-switched mode-locked pulse train with respect to the pump power for sample 1

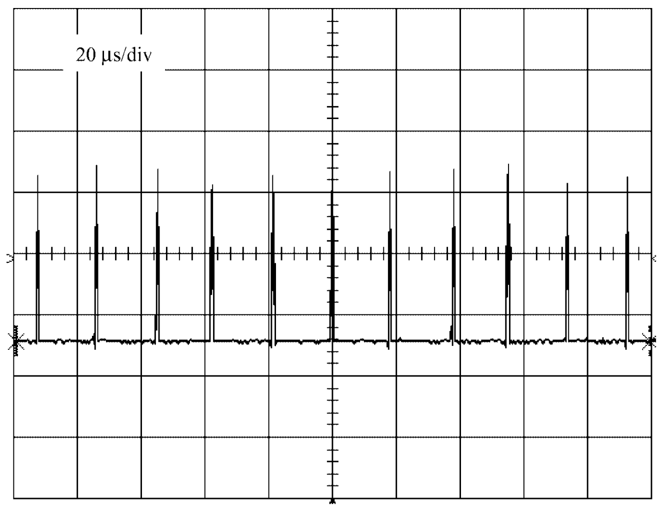

Fig. 3. Oscilloscope traces of a train of Q-switched pulses for sample 1

and that there was no satellite pulse between the mode-locked pulse trains. The mode-locked pulse duration inside the Q-switched pulse was measured using an autocorrelator (KTP type II interaction) in collinear configuration. Note that we only measured the average pulse duration because it is difficult to characterize single mode-locked pulses underneath the Q-switch envelope. The temporal duration of the mode-locked pulses was measured to be about 75 ps, as shown in Fig. 5. The peak power of a single pulse near the maximum of the Q-switched envelope was around 4 kW.

With sample 2, a 100% depth of mode-locking could also be obtained. The Q-switched pulse envelope had a temporal duration of approximately 180 ns. At an absorbed pump power of 23.6 W, the average output power was 3.5 W and the repetition rate of the Q-switched pulse was 160 kHz. Although the maximum average output power with the sample 2 was lower, the peak power was two times higher than the

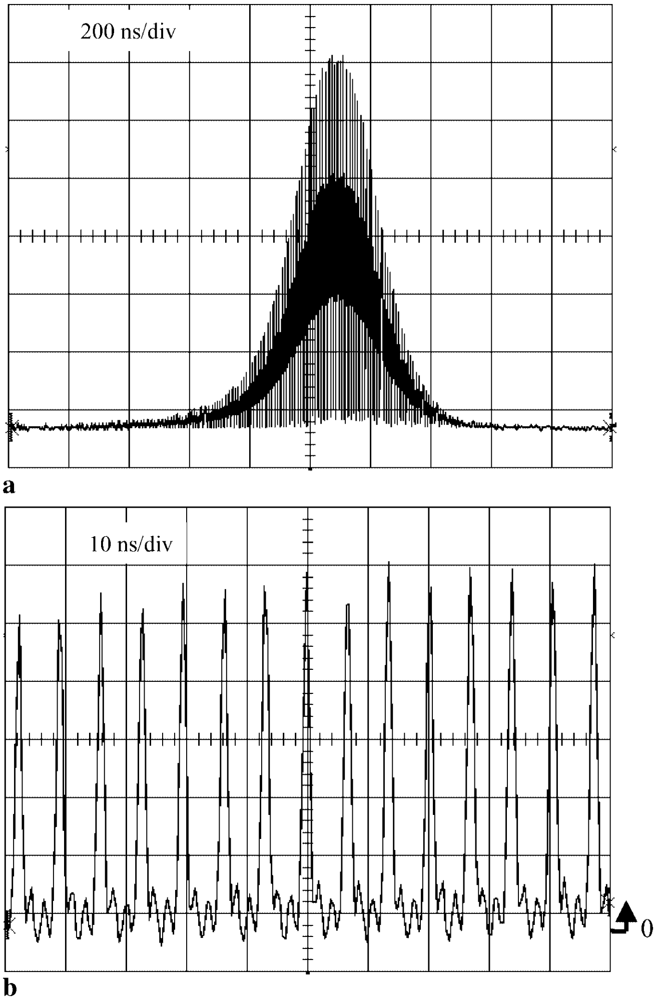

Fig. 4. a Expanded temporal shape of a single Q-switched pulse for sample 1. **b** Oscilloscope traces of a train of mode-locked pulses for sample 1

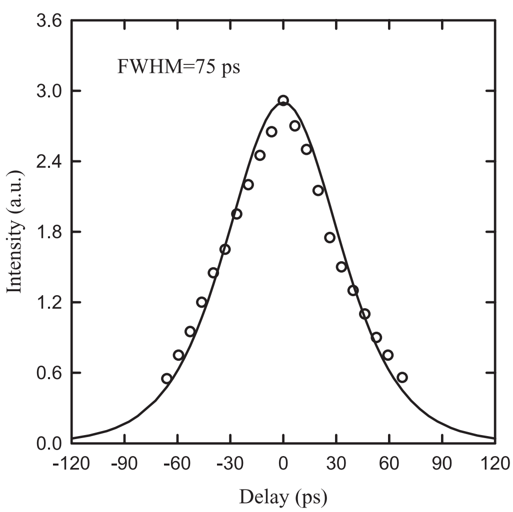

Fig. 5. Autocorrelation trace of the Q-switched mode-locked pulse

result obtained using sample 1. Therefore, we believe that a higher peak power can be obtained using a LiF:F_2^- absorber with a lower initial transmission. Moreover, the timing jitter and the peak-to-peak amplitude fluctuation of the Q-switched envelope can be less than ±10% at the full pump power. During the experiment, the temperature rise of the LiF:F_2^- absorber was not significant and no optical damage to the absorber was observed. Temperature control of the LiF:F_2^- absorber was necessary because it can be thermally destroyed above 75 °C.

We used different output couplers ($R = 55\%$ and 90%) in the present cavity to investigate the dependence of mode-locked operation on the output reflectivity. It was found that the Q-switched envelope depended on the output reflectively but the modulation depth of mode-locking was independent of the coupler. 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 the temporal shape of the Q-switched and mode-locked pulses were barely influenced by the change of the beam size in the absorber. It has also been found that the mode-locking operation is insensitive to the alignment of the absorber. Therefore, the key parameter for temporal shape of the Q-switched envelope is the initial absorber transmission.

For comparison, we also replaced the LiF:F_2^- absorber by a Cr^{4+}:YAG crystal with $T_0 \approx 90\%$. Since the absorption cross section in this case is not high enough, we placed the Cr^{4+}:YAG crystal 0.5 cm from the output coupler, in order to obtain good operation. The lasing threshold and optical slope efficiency were found to be 3.5 W and 35.6%, respectively. As compared with the performance of the LiF:F_2^- absorber with the same initial transmission, the threshold was lower and the slope efficiency was higher. These results mean that the Cr^{4+}:YAG crystal introduces less unsaturable losses than the LiF:F_2^- absorber. The Q-switched pulse envelope and the mode-locked pulses inside the Q-switched pulse are shown in Fig. 6a and b, respectively. Although the modulation depth of the mode-locking was also completely full (100%), there were some satellites between mode-locked pulse trains. The average mode-locked pulse duration (FWHM) was measured to be about 120 ps, which was substantially longer than the result obtained with the LiF:F_2^- absorber. This result indicates that the Cr^{4+}:YAG absorber results in a longer pulse build-up time than the LiF:F_2^- absorber.

The fluctuation mechanism is believed to be mainly responsible for generating ultrashort pulses in Q-switched lasers having non-linear absorbers [13, 14]. According to this mechanism, ultrashort pulse formation is accounted for as follows: In the linear stage of generation, the fluctuations in 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 non-linear 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 [14] used the fluctuation mechanism to prove that the ratio of peak pulse power to the mean background power can be given by

$$\frac{P_m}{P_{\text{backgr}}} \cong (\ln m)^{\mu} , \tag{1}$$

where m is the number of axial modes at the end of the linear stage of build-up and μ is the non-linear parameter related to the pulse compression in the non-linear stage of the development. To obtain a high pulse-to-background ratio, m and

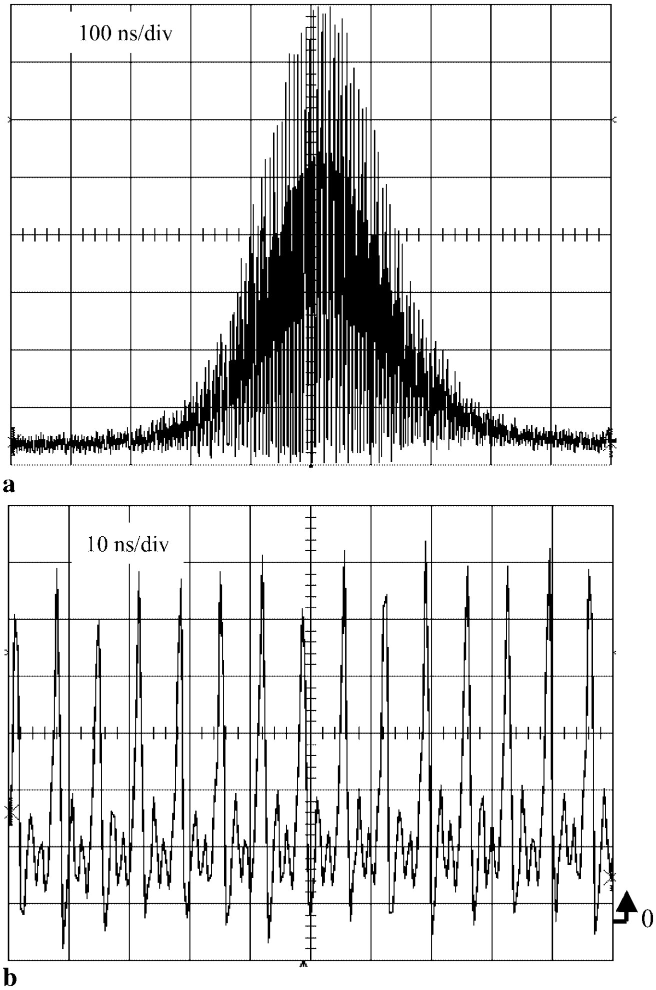

Fig. 6. **a** Expanded temporal shape of a single Q-switched pulse with the Cr^{4+}:YAG absorber. **b** Oscilloscope traces of a train of mode-locked pulses with the Cr^{4+}:YAG absorber

μ should be as large as possible. During the linear stage of the intensity fluctuation build-up, the number of axial modes decreases due to the natural selection towards the center of amplification line given by [14]:

$$m = \frac{m_0}{(\alpha_0(t_b/t_r))^{1/2}}\,, \tag{2}$$

where m_0 is the initial number of axial modes, α_0 is the threshold gain, t_r is the round-trip transit time of light in the cavity, and t_b is the pulse build-up time. In most cases the non-linear parameter is given by [14]

$$\mu = \frac{1 - T_0}{t_b(\mathrm{d}\alpha/\mathrm{d}T)}\,, \tag{3}$$

where T_0 is the initial transmission of the saturable absorber and $\mathrm{d}\alpha/\mathrm{d}t$ is the rate of the gain increase due to pumping at the time of threshold. From (1)–(3) it can be found that a shorter pulse build-up time generally leads to a larger m and a larger μ, resulting in a higher pulse-to-background ratio.

3 Conclusions

In conclusion, we have demonstrated the use of a LiF:F_2^- absorber for obtaining a high-power diode-pumped Nd:YVO_4 laser in a Q-switched mode-locked mode, to our knowledge for the first time. A 100% depth of mode-locking is obtained and there is no satellite pulse between mode-locked pulse trains. Experimental results also show that the Cr^{4+}:YAG absorber leads to a higher conversion efficiency, whereas the LiF:F_2^- absorber results in a shorter mode-locked pulse duration in the diode-pumped Q-switched and self-mode-locked Nd:YVO_4 laser.

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