Passive Q-Switching of a Yb:$LuVO_4$ Laser with Cr^{4+}:YAG: Approaching the Intrinsic Upper Limit of Repetition Rate *

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We demonstrate a diode pumped Yb:$LuVO_4$ laser that can be passively Q-switched by a Cr^{4+}:YAG saturable absorber having an initial transmission as high as 99.3%. A maximum pulsed output power of 2.35 W is generated at a repetition rate of 285.7 kHz, approaching or very near the intrinsic upper limit imposed by the recovery time of the Cr^{4+}:YAG saturable absorber, and the resulting pulse energy, duration and peak power are, respectively, 8.2 μJ, 39.2 ns and 0.209 kW.

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The tetragonal orthovanadates, including YVO_4, $GdVO_4$ and $LuVO_4$, constitute one of the most important classes of host crystals for trivalent rare-earth active ions, which is particularly the case for Nd ions. In fact, except for the garnet family represented by the well-known YAG ($Y_3Al_5O_{12}$), few other known host crystals can compete with these orthovanadates for making Nd-ion laser materials.[1] The situation for the ytterbium (Yb) ion, however, turns out to be quite different. In contrast to the numerous extensive as well as intensive studies on the Nd-ion doped orthovanadates that have been made since the advent of diode lasers as a pumping source, much less work has thus far been conducted on these vanadate crystals doped with Yb-ions, although they appeared as early as more than a decade ago.[2–5] As a matter of fact, even in the continuous-wave (cw) regime the maximum output power amounted to only 10–13 W, which was generated in thin-disk configuration;[6] while the output power produced with these Yb:vadadate lasers under usual longitudinal pumping conditions is still limited to a 5–8 W level.[7,8] Studies on the Q-switching laser properties of these Yb:vanadates are even more insufficient. Up to now, passive Q-switching operation with Cr^{4+}:YAG serving as a saturable absorber was realized only in Yb:YVO_4 lasers, with pulsed output power producing less than 1 W;[9,10] while for Yb:$LuVO_4$, only graphene passively Q-switched laser action was achieved, generating 0.3 W of pulsed output power.[11]

In this Letter, we report a Yb:$LuVO_4$ crystal laser that is passively Q-switched by a Cr^{4+}:YAG saturable absorber. Stable repetitively pulsed laser operation could be realized utilizing a very thin Cr^{4+}:YAG crystal plate whose initial transmission (T_0) is as high as 99.3% (modulation depth as small as 0.7%); more than 2 W of average output power could be produced at extremely high repetition rates, very close to the intrinsic limit imposed by the recovery time of the Cr^{4+}:YAG saturable absorber. It is the first time that the upper limit of the repetition rate was approached in Cr^{4+}:YAG passively Q-switched lasers.

The crystal sample of Yb:$LuVO_4$ utilized in the experiment was *a*-cut, 2 mm long, with a square aperture of 3.3 mm × 3.3 mm. The Yb-ion concentration in the crystal was 1.96×10^{20} cm^{-3} (1.5 at.%), and no antireflection (AR) coatings were placed on the end faces of the crystal sample. This would not introduce noticeable reflection losses, which would be greatly diminished by some etalon effects existing in the cavity. As the saturable absorber for passive Q-switching, two Cr^{4+}:YAG crystal plates having thicknesses of 0.19 and 0.80 mm, and initial transmissions of $T_0 = 99.3\%$ and $T_0 = 97.5\%$ (at the wavelength of 1030 nm), were employed. Both were AR coated on their surfaces for a central wavelength of 1030 nm. To make the Q-switched Yb:$LuVO_4$ laser, a Plano-concave resonator was utilized. The plane mirror was coated for high reflectance (>99.9%) at wavelengths of 1020–1200 nm, and for high transmittance (>95%) at 976 nm; whereas the concave mirror, having a radius of curvature of 25 mm, served as the output coupler, whose transmission (output coupling) was $T = 10\%$ at 1030 nm. Inside the resonator, the laser crystal was positioned near the plane mirror, and the saturable absorber was inserted between the laser crystal and the output coupler. The cavity length was 23 mm. A fiber-coupled diode laser emitting at 976 nm (STL976T2-50W, STONE Laser, China) was used to pump the Yb:$LuVO_4$ laser, and the fiber core diameter and NA were, respectively, 100 μm and 0.22. The pump beam was first focused by a re-imaging unit and then was delivered through the plane mirror into the laser crystal, with a pump spot of about 50 μm in radius. Other instruments employed for measurements included: a power meter (S/N:210276, Gentec-eo); a spectrometer (SR-500i-B1, ANDOR); an oscilloscope (S/N:MY46002199, Agilent Technologie); and a beam

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quality analyzer (M2-200S-USB, Spiricon).

We first measured the absorption spectrum of the two Cr^{4+}:YAG crystal plates utilized as saturable absorbers in the experiment. Figure 1 depicts the absorption spectra in terms of absorbance, i.e., the optical density (O.D.) over a wavelength range of 900–1150 nm.

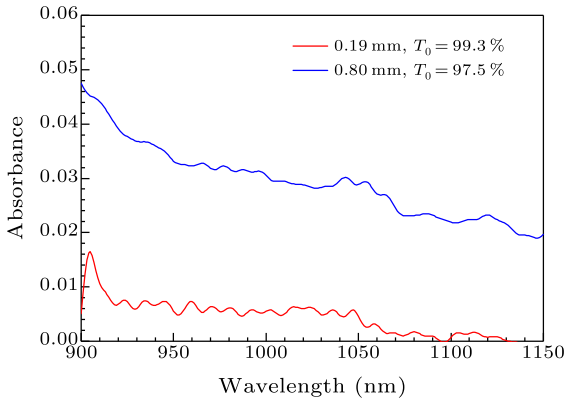

Fig. 1. Absorbance versus wavelength measured for the two Cr^{4+}:YAG crystal plates with different thicknesses.

Passively Q-switched operation of the Yb:$LuVO_4$/Cr^{4+}:YAG laser was achieved under the condition of $T_0 = 99.3\%$ or $T_0 = 97.5\%$. In both cases the optimal output coupling proved to be $T = 10\%$. Figure 2 shows the average output power as a function of the absorbed pump power ($P_{\rm abs}$) produced under the two different Q-switching conditions. For comparison, the cw output power versus $P_{\rm abs}$ is also presented. One sees that in Q-switched laser action for $T_0 = 99.3\%$, the pulsed output power at a given pumping level is only slightly lowered in comparison with that generated in cw operation, and it increases roughly linearly with $P_{\rm abs}$, with a slope efficiency of $\eta = 25\%$. One notes that in excess of $P_{\rm abs} \approx 10$ W, the Q-switched laser operation becomes less efficient, and this results from the enhancement of thermally induced loss. As can be seen, similar behavior also occurs above this specific pumping level in the cw laser action. The maximum average output power 2.35 W was produced at $P_{\rm abs} = 11.6$ W, with an optical-to-optical efficiency of 20.3%. With the pumping level raised further, no more output power could be generated, and the passive Q-switching laser performance begins to deteriorate. The reason for this will be given in the following. Under conditions of $T_0 = 97.5\%$, the threshold for Q-switching laser action is reached at $P_{\rm abs} = 2.25$ W, above which the pulsed output power could increase linearly at the initial stage, and would eventually become rolling off. The highest average output power that could be generated in this case is 0.93 W.

The quality of the laser beam is examined. The inset of Fig. 2 shows a laser beam pattern measured at $P_{\rm abs} = 5.7$ W. The beam quality factor M^2 is determined to be 1.14 in the horizontal direction, and 1.16 in the vertical direction.

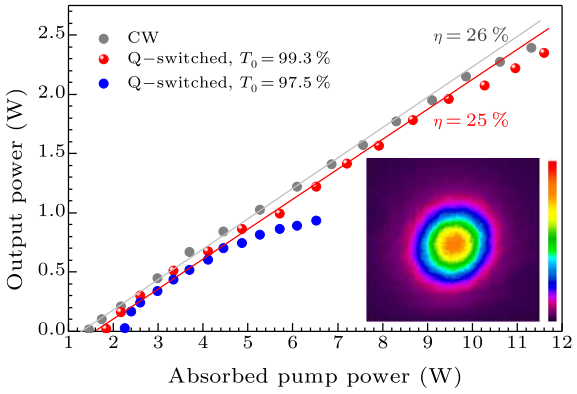

Fig. 2. Average output power versus absorbed pump power measured under different Q-switching conditions. Inset: laser beam pattern measured at $P_{\rm abs} = 5.7$ W.

For Q-switched or cw laser operation, the emission spectrum varies only slightly with the pumping level. Figure 3 illustrates the lasing spectrum measured at $P_{\rm abs} = 6.5$ W, for the cw and the two different Q-switched laser operations. Under passive Q-switching conditions of $T_0 = 99.3\%$, the laser action occurred over a wavelength region of 1023.5–1028.3 nm, nearly overlapping with the cw lasing spectrum, because of the closeness in overall resonator losses in the two cases. In Q-switched operation induced by the saturable absorber of $T_0 = 97.5\%$, the lasing spectrum shifts to a shorter wavelength region of 1021.0–1022.7 nm. With the change of Cr^{4+}:YAG from $T_0 = 99.3\%$ to $T_0 = 97.5\%$, the overall resonator losses increase due to the increase of the saturable loss. As a result, a higher gain is required to reach the lasing threshold, thus forcing the laser action to shift to those shorter wavelengths where the gain reaches its maximum.

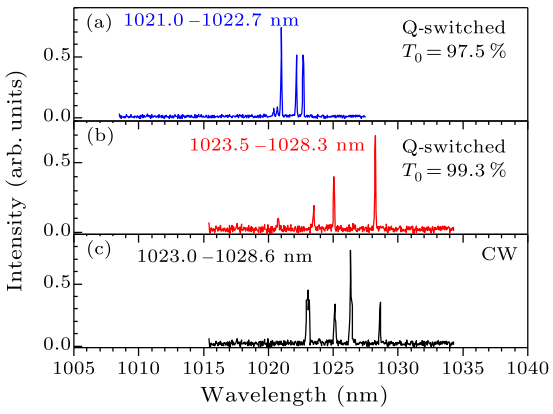

Fig. 3. Emission spectra measured at $P_{\rm abs} = 6.5$ W for cw and Q-switched laser operations.

Figure 4 depicts the dependence of pulse repetition rate on the absorbed pump power for the two Q-switched laser operations. In the case of $T_0 = 97.5\%$, the repetition rate increases from 28.0 kHz, measured just above the Q-switching threshold, to 75.0 kHz at $P_{\rm abs} = 6.5$ W, the highest pumping level is applied

in this case. The pulse repetition rates are proved to be much higher under the passive Q-switching conditions of $T_0 = 99.3\%$. Because of the very small modulation depth amounting only to 0.7%, the time taken for the gain to be accumulated to balance the overall losses would be much shorter than that in the case of $T = 97.5\%$, leading to much higher repetition rates. Also, because of this very small modulation depth, larger irregularity is observed in the increase of repetition rate with the rising pump power. One sees that the repetition rate increases, from 40.5 kHz at $P_{\rm abs} = 2.1$ W near the threshold, roughly linearly with the pump power, to 200.0 kHz at $P_{\rm abs} = 8.3$ W. Above this pumping level, the variation of repetition rate becomes more irregular. One notices that the time interval between two successive pulses, 5 μs, has already been comparable with the recovery time of the Cr^{4+}:YAG saturable absorber which is known to be 4.1 μs.[12] With the pump power being raised continually, the resulting pulse repetition rate would continue to rise, making the time interval closer and closer to the recovery time. As a consequence, the repetition rate would be affected increasingly by the extent to which the saturable absorber has recovered from bleaching. This would give rise to additional irregularity. The repetition rate measured at $P_{\rm abs} = 11.6$ W, at which the maximum pulsed output power is produced, is 285.7 kHz; whereas the highest repetition rate is measured, at $P_{\rm abs} = 11.3$ W, to be 294.1 kHz, corresponding to a pulse time interval of 3.4 μs. This time interval appears to be shorter than the recovery time mentioned above for the Cr^{4+}:YAG saturable absorber. It should be pointed out, however, that during the passive Q-switching laser operation, a substantial temperature rising would occur inside the Cr^{4+}:YAG crystal. Due to the strong electron–phonon coupling characteristic of the Cr^{4+}:YAG crystal,[13] the non-radiative decay rate will be enhanced with rising the temperature, leading to considerable reduction in the overall lifetime (or fluorescence lifetime) of the metastable level, which is the same thing as the recovery time termed for the Cr^{4+}:YAG saturable absorber. An intensive investigation shows that with crystal temperature raised from 20 to 50℃, the recovery time of the Cr^{4+}:YAG saturable absorber would be reduced from about 4.6 μs to about 3.3 μs.[13] Given that during the passive Q-switching laser action achieved in our experiment, the actual temperature inside the Cr^{4+}:YAG crystal also varies over a similar temperature range, we can estimate the intrinsic upper limit of pulse repetition rate, which could at most be reachable from the current Yb:$LuVO_4$/Cr^{4+}:YAG passively Q-switched laser. By assuming a minimum recovery time of 3.3 μs, one can estimate the upper limit of repetition rate to be roughly 300 kHz, since the time interval between two successive laser pulses must be longer than the recovery time of the saturable absorber. One sees that the pulse repetition rates, which are reached at high pumping levels of $P_{\rm abs} > 11$ W, have already been very close to this upper limit.

Illustrated in Fig. 5 are a few typical laser pulse trains recorded at $P_{\rm abs} = 9.5$, 11.0, and 11.6 W in the case of $T_0 = 99.3\%$. One sees that as the repetition rate approached its upper limit, both pulse amplitude fluctuations and timing jitters increased. For example, at 196.1 kHz where the pulsed laser operation is far from this upper limit, the temporal stability, i.e., the timing jitters, is about 12%; while the intensity stability or the amplitude fluctuation is roughly 3%. When the laser operated at 285.7 kHz, these two stability parameters are approximately 20% and 15%, respectively.

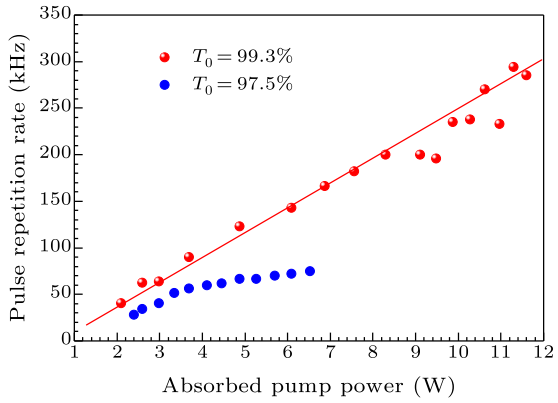

Fig. 4. Pulse repetition rate versus $P_{\rm abs}$ for the two passively Q-switched laser operations.

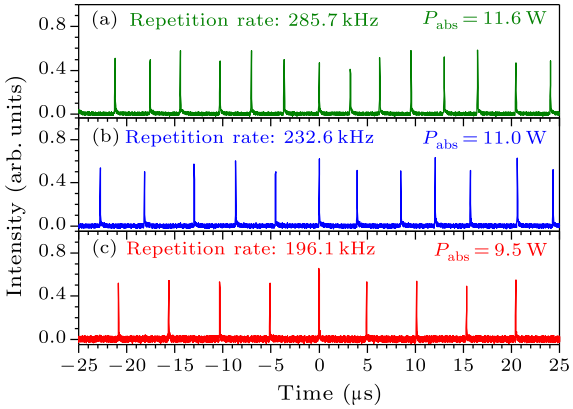

Fig. 5. Pulse trains recorded at $P_{\rm abs} = 9.5$, 11.0, and 11.6 W in the case of $T_0 = 99.3\%$, showing an evolution toward the upper limit of repetition rate.

Figure 6 shows the variation of pulse energy with absorbed pump power under the two different Q-switching conditions. In both the cases the pulse energy increases initially with the pumping level, eventually reaching a certain value that remains nearly unchanged. For $T_0 = 97.5\%$, the final pulse energy is measured to be 12.4 μJ; while in the case of $T_0 = 99.3\%$, this energy is estimated to be 8.2 μJ. Compared with the case of $T_0 = 97.5\%$, the pulse energy produced in the case of $T_0 = 99.3\%$ is proved to be considerably lower because of the less stored energy that could be accumulated via pumping during

the time interval between two successive pulses. One can notice that in excess of $P_{abs} \approx 8.5$ W, the pulse energy varies, in the vicinity of 8.2 μJ, irregularly with the pump power. Such variations are connected to the irregularity exhibited in the rising of repetition rate with the pump power over the same pumping region (Fig. 4).

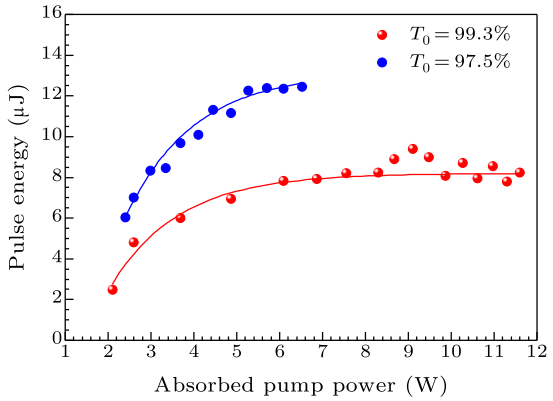

Fig. 6. Pulse energy versus P_{abs}, generated in the two passively Q-switched laser operations.

Unlike the pulse energy which, at the initial stage of the Q-switched laser action not far above the threshold, changed substantially with pumping level, the pulse duration is found, in the case of $T_0 = 99.3\%$, only decreasing moderately, from 53.0 ns near the lasing threshold to 39.2 ns at $P_{abs} = 11.6$ W; while in the case of $T_0 = 97.5\%$, the pulse duration remains almost unchanged (21.5–22.0 ns) over the entire operational region. Figure 7 shows the pulse profiles, which are measured at $P_{abs} = 11.6$ W for the case of $T_0 = 99.3\%$; and at $P_{abs} = 6.5$ W for the case of $T_0 = 97.5\%$. One notes that the pulse duration for $T_0 = 97.5\%$ is roughly one half the pulse duration for $T_0 = 99.3\%$. Such reduction in pulse duration is attributed to the enhancement of initial population inversion density in the case of $T_0 = 97.5\%$. According to a simple theoretical model for Q-switched lasers, the minimum pulse duration achievable is inversely proportional to the initial inversion density.[15]

From the experimental results presented above, one notices the great difference in the pulsed laser characteristics obtained with the two Cr^{4+}:YAG crystals. Thermal effects, which are expected to differ for the two crystal plates of different thicknesses, may have some influence on the passive Q-switching process. However, the most important reason for such difference is the different values of modulation depth, $1 - T_0$, which play an essential part in passive Q-switching laser action.

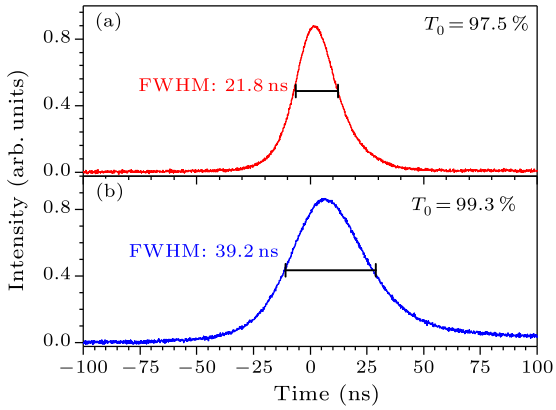

Fig. 7. Pulse profiles recorded at $P_{abs} = 6.5$ W in the case of $T_0 = 97.5\%$ (a); and at $P_{abs} = 11.6$ W in the case of $T_0 = 99.3\%$ (b).

Table 1. Comparison of passive Q-switching performance between the Yb:$LuVO_4$/Cr^{4+}:YAG laser and the previously reported Yb:$LuVO_4$/graphene laser.

Laser	PRR (kHz)	P_{max} (W)	E_p (μJ)	t_p (ns)	P_p (kW)	η_s (%)	λ (nm)
Yb:$LuVO_4$/Cr^{4+}:YAG	285.7	2.350	8.20	39.2	0.209	25	1023.5–1028.3
Yb:$LuVO_4$/graphene[a]	270.0	0.155	0.57	190.0	0.003	9	1021.0
Yb:$LuVO_4$/graphene[b]	330.0	0.310	0.94	240.0	0.004	17	1021.0

[a]From Ref. [11], plano-concave resonator, $T = 10\%$, and [b] From Ref. [11] plano-plano resonator, $T = 10\%$.

We have demonstrated that the Yb:$LuVO_4$ laser could be passively Q-switched by a Cr^{4+}:YAG saturable absorber with an initial transmission as high as $T_0 = 99.3\%$, generating stable pulses at very high repetition rates approaching the upper limit. Passive Q-switching laser action, which could be induced by a Cr^{4+}:YAG saturable absorber having such a high initial transmission, was previously realized only with a Yb:YVO_4 laser.[10] However, the highest repetition rate reached in that laser amounted only to 71.4 kHz; and the pulsed output power was limited to 0.87 W.[10] To our knowledge, the highest repetition rate achieved thus far from passive Q-switching by the Cr^{4+}:YAG saturable absorber is 252 kHz, which was reached in a Nd:$GdVO_4$ bounce laser operating under conditions of $T_0 = 45\%$.[14]

It may be of some interest to make a comparison with the recently reported Yb:$LuVO_4$ laser that was passively Q-switched by a single-layer graphene saturable absorber, where, except for the much shorter cavity length (4 mm), the Yb:$LuVO_4$ crystal sample, the pumping conditions, as well as the resonator configuration, were either identical or very similar to those used in the current experiment.[11]

Table 1 lists the primary parameters characterizing the performance of a passively Q-switched laser, for the current Yb:$LuVO_4$/Cr^{4+}:YAG laser operating under the conditions of $T = 10\%$, $T_0 = 99.3\%$; and for the previous Yb:$LuVO_4$/graphene lasers.[11] The notations used in the table are: PRR, pulse repeti-

tion rate; $P_{\max}$, maximum average output power; $E_{\rm p}$, pulse energy; $t_{\rm p}$, pulse duration; $P_{\rm p}$, peak power; η, slope efficiency; and λ, lasing wavelength. One can notice that while the highest repetition rates achieved were comparable, much shorter pulse duration was obtained here, and the average output power, the pulse energy, or the peak power generated from the Yb:$LuVO_4$/Cr^{4+}:YAG laser proved to be roughly one or two orders of magnitude higher than that produced with the Yb:$LuVO_4$/graphene laser.

In summary, stable pulsed operation has been demonstrated in a Yb:$LuVO_4$ laser that is passively Q-switched by a Cr^{4+}:YAG saturable absorber with an initial transmission as high as 99.3%. An average output power of 2.35 W is produced at a pulse repetition rate of 285.7 kHz, approaching or near the intrinsic upper limit imposed by the recovery time of the Cr^{4+}:YAG saturable absorber; and the resulting pulse energy, duration, and peak power are, respectively, 8.2 µJ, 39.2 ns, and 0.209 kW. Pulsed operation at such high repetition rates turns out to be quite rare among Yb-ion lasers passively Q-switched by a Cr^{4+}:YAG saturable absorber. Therefore, it is worthwhile to investigate other Yb:vanadate/Cr^{4+}:YAG lasers to improve the high-repetition-rate pulsed laser performance for potential applications.

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