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Presentation of a new and simple technique of *Q*-switching with a $LiSrAlF_6$:Cr^{3+} oscillator

B.C. Weber, A. Hirth

French–German Research Institute Saint-Louis, 5, rue du général Cassagnou, B.P. 34, 68301 Saint-Louis Cedex, France

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Abstract

A new technique of *Q*-switching is presented which is characterized by the fact that no additional switch (Pockels cell, saturable absorber, etc.) is required in the resonator. It can be shown that the effectiveness of the switching strongly depends on the resonator geometry, the position of the laser medium in the resonator and the features of the laser medium itself: Using a near-hemispherical resonator including a $LiSrAlF_6$:Cr^{3+} rod which is located pretty close to the curved mirror we obtained laser pulses with energies of 60 mJ and widths of about 200 ns. © 1998 Elsevier Science B.V.

Keywords: Cr:LiSAF laser; *Q*-switching; Self-*Q*-switching; Dispersion

1. Introduction

Q-switching is a widely used technique which allows to transform the pump energy (or at least a part of it) deposited in the laser medium usually over a longer period of time into an intense single short laser pulse with a width of typically only a few tens up to a few hundreds of nanoseconds. There are different common *Q*-switching methods including rotating mirror *Q*-switching, electrooptic *Q*-switching, acoustooptic *Q*-switching and so on. A disadvantage of all these methods is that they need an external driving circuitry. Some of them require supplementary optical elements inside the resonator causing additional expense and costs. An alternative is represented by passive saturable-absorber *Q*-switching which is often executed by absorbing dyes. The disadvantage of this method however is that these dyes may be subject to chemical or photochemical degradation.

All these mentioned *Q*-switching techniques require an additional switch inside the laser. In contrast to these methods we present a new technique which can renounce to any form of supplementary element in the resonator and which is therefore simple, convenient and cheap.

2. Experimental setup and results

The experimental setup is shown in Fig. 1 and described in detail in Ref. [1]. Using a near-hemispherical resonator we obtain a good exploitation of the 3 mm × 55 mm $LiSrAlF_6$:Cr^{3+} rod by the fundamental mode when installing the laser medium close to the HR mirror (in the experiment: $d_1 = 0.11$ m). Applying a six-mesh network nearly rectangular pump pulses with a duration of 60 μs can be created while the energy per pump pulse can be tuned from 0 to nearly 15 J.

The laser pulse generation works as demonstrated in Fig. 2: for a given resonator length (in Fig. 2 for instance $L = 1.4$ m) the pump energy is increased so far that the first single spike which appears at the end of the pump pulse contains a maximum of energy. On the other hand

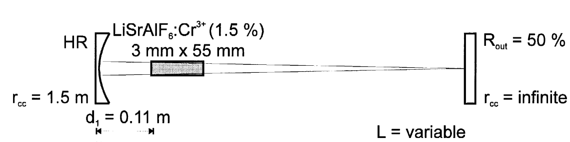

Fig. 1. Experimental setup.

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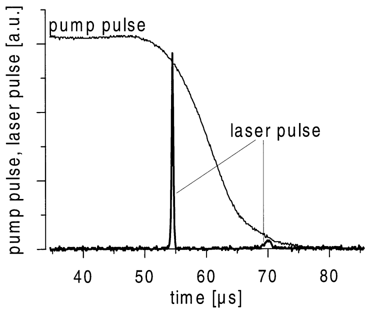

Fig. 2. Laser pulse generation: emerging single spikes (thick line) at the end of the pump pulse (thin line) when the pump energy is high enough.

the upper limit of the pump energy is given by the demand to suppress the second spike which just appears in Fig. 2 at about 15 μs after the first one (so, the pump energy has to be reduced a little bit).

Using the resonator configuration shown in Fig. 1 we measured the pulse energy and widths (FWHM) for different resonator lengths. The results are shown in Fig. 3 (of course, proceeding in the way described above, increasing the resonator length requires an increasing of the pump energy since the resonator losses are growing). Thereby the laser oscillated at a center wavelength of $\lambda = 830$ nm and in the fundamental mode.

3. Discussion

Remarkable in Fig. 3 is the exceptionally strong growth of the energy per pulse when increasing the resonator length. At the same time the pulse width is getting shorter and shorter. In Ref. [1] it was demonstrated that this phenomenon cannot solely be explained by the growing transmitted crystal volume by the fundamental mode. Comparing these results with those demonstrated in Refs. [2,3], where Cr:LiSAF is *Q*-switched one can see strong similarities. So it seems that the oscillator presented here is also *Q*-switched although it does not contain any additional switch (Pockels cell, saturable absorber, etc.).

4. Switching mechanism and requirements

Increasing the resonator length when using the setup shown in Fig. 1 does not only provide a better exploitation of the rod volume by the fundamental mode but also delivers growing losses due to truncation of the edges of the beam by the rod's aperture. Fig. 4 shows the dependence of the spot size w at the rod on the resonator length L when keeping the distance between HR mirror and laser medium constant ($d_1 = 0.11$ m), and Fig. 5 shows the resulting resonator losses caused by the rod aperture which were calculated in Ref. [4]. High initial losses – here: beam truncation losses at the aperture of the rod – are a necessary assumption for *Q*-switching in order to store pump energy in the laser crystal.

After this storing process the losses must be diminished in a more or less short period of time. Diminution of the losses at the aperture of the rod can only take place by reducing the radius of the fundamental mode in the region of the rod (since the radius of the aperture does not change). This process is carried out by a negative lens developing in the laser crystal. Fig. 6 demonstrates the consequences of a negative lens with different focal lengths to the spot size w of the fundamental mode along the resonator axis assuming this lens at the place of the rod in Fig. 1. It becomes obvious that a decreasing focal length causes a reduction of the beam radius in the region of the lens (= rod in the experiment) and therefore a diminution of the beam truncation losses at the aperture of the rod.

The origin of this lens can be explained as follows:

The dispersion theory shows a strong dependence of the real part of the refractive index on the density of the absorbing particles of the transmitted medium in the vicinity of the resonance frequency ω_0. Leaving this region this

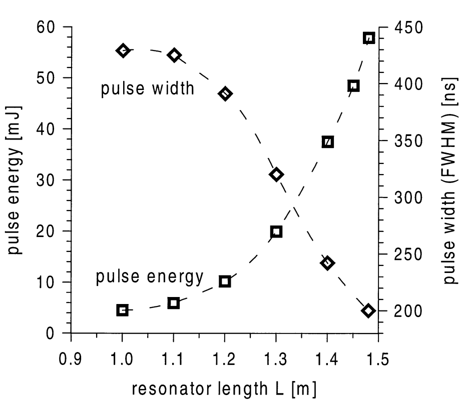

Fig. 3. Pulse energy and corresponding pulse width versus resonator length L using the setup of Fig. 1.

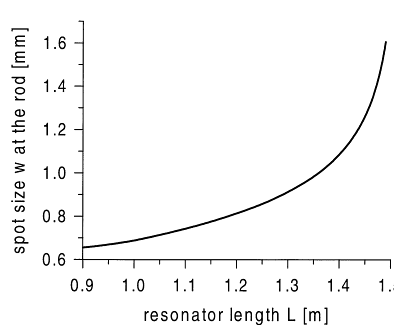

Fig. 4. Spot size w at the rod versus resonator length L using the setup of Fig. 1.

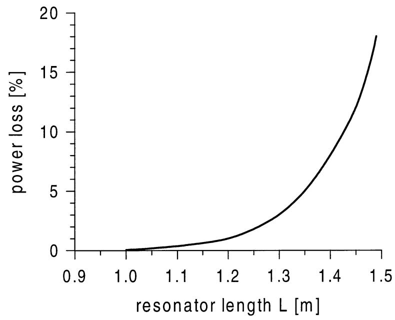

Fig. 5. Power loss at the aperture of the rod per round-trip versus resonator length L using the setup in Fig. 1.

dependence becomes weaker and weaker. This regularity can be seen in Fig. 7: starting from a dispersion curve as it can be found e.g. in Ref. [5] the density of the absorbing particles n_S was doubled ($2n_S$), tripled ($3n_S$), etc. $LiSrAlF_6:Cr^{3+}$ shows a pretty strong excited-state absorption (ESA) within its emission band [6,7] which means some of the chromium ions in the excited-state are subjected to another excitation in higher states by absorbing photons which are generated by stimulated emission. The values of the cross sections of these transitions lie in the same order of magnitude as those of the stimulated emission [6]. The build-up of the laser pulse leads to a reduction of the population inversion which is identical to a decrease of the absorbing particles of the ESA transition. Appropriate to the dispersion theory this means close to the resonance frequency ω_0 and therefore in the region of the emission band of $LiSrAlF_6:Cr^{3+}$ a relatively strong change in the refractive index.

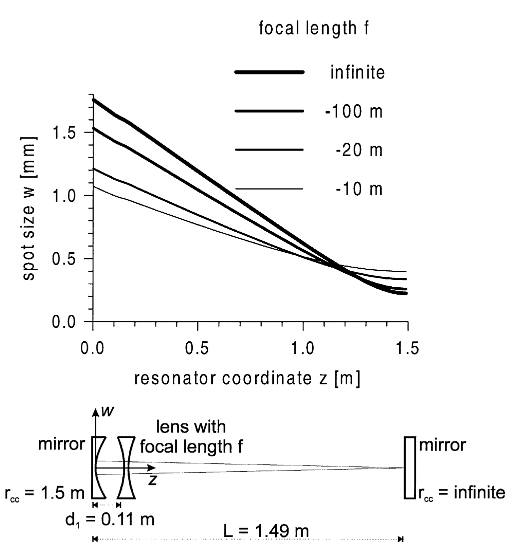

Fig. 6. Spot size w of the fundamental mode along the resonator axis for different focal lengths of the lens assumed in the rod. Setup: lens close to the curved mirror.

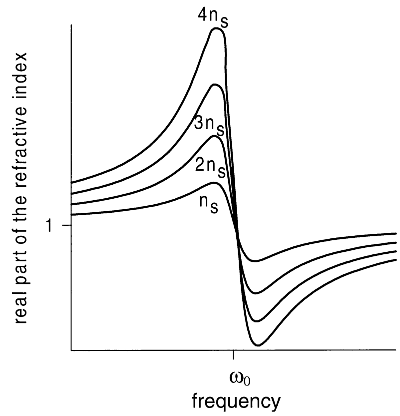

Fig. 7. Real part of the refractive index versus frequency for different densities n_S of the absorbing particles in the transmitted medium (ω_0 = resonance frequency).

The laser oscillates in the fundamental mode with a spatial intensity distribution as presented in Fig. 8 (detected at a resonator length of $L = 1.4$ m at a distance from the flat mirror of about 7 m; xy-plane perpendicular to the resonator axis). The resulting reduction of the inversion density which is in the same way not constant across the rod cross section delivers a refractive index profile in the rod with the effect of a negative lens. Following it there is a decrease of the beam diameter in the region of the rod (see Fig. 6) and therefore a diminution of the diffraction losses. Consequently, the build-up of the laser pulse will be amplified, the profile of the refractive index is getting stronger and so on. So, what can be observed is a form of self-Q-switching which is started and conducted by the laser pulse itself. Concerning this point of view the switching mechanism is comparable with that one executed by a saturable absorber.

So far, the dependence of the effectiveness of the Q-switching on the features of the laser crystal was demonstrated: basic requirement is a laser medium whose emitted radiation is subjected to a strong absorption while the density of the absorbing particles undergoes a change

Fig. 8. Typical spatial intensity distribution of the laser pulse obtained with the setup of Fig. 1 (resonator length $L = 1.4$ m).

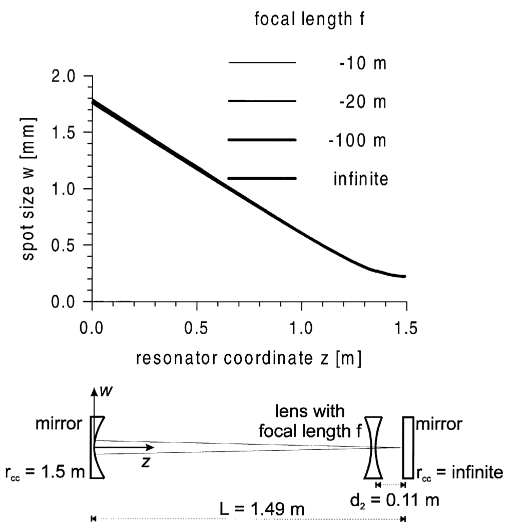

Fig. 9. Spot size w of the fundamental mode along the resonator axis for different focal lengths of the lens assumed in the rod. Setup: lens close to the flat mirror.

with the build-up of the laser pulse (e.g. ESA at $\lambda_{emission}$ by the excited particles in the upper laser level).

Besides this, the switching mechanism strongly depends on the resonator configuration and the position of the laser medium in the resonator as can be seen in the following:

Dependence on the position of the laser medium in the resonator: The effectiveness of the negative lens concerning the reduction of the spot size w in the region of the lens (= rod) when locating the lens close to the curved mirror was demonstrated in Fig. 6. A completely different result is obtained when shifting the lens away from the curved mirror close to the flat mirror ($d_2 = 0.11$ m) as presented in Fig. 9. Reducing the focal length of the lens in the same way as in Fig. 6 has nearly no effect on the beam radius along the whole resonator axis. So, no diminution of beam truncation losses at any aperture along the resonator axis and consequently no switching effect can be expected.

Dependence on the resonator configuration: Returning to the setup of Fig. 1 (that is $d_1 = 0.11$ m), Fig. 10 demonstrates how strongly the spot size at the laser rod is reduced when increasing the refraction power of the lens which is assumed to build-up in the rod. This development is presented for different resonator lengths. One can see that when the resonator approaches the boundary of the stability region which corresponds to $L = 1.5$ m it becomes more and more sensitive to changes of the focal length of the lens in the rod in the sense that the changes of the spot size w at the rod aperture grow. In the same way the losses caused by the rod's aperture change more and more and consequently a more effective switching mechanism should be practicable.

5. Confirmation of the theory by experiments

Actually, this latter prediction was already confirmed by the results presented in Fig. 3. There, one could observe strongly growing pulse energies and decreasing pulse widths when increasing the resonator length which is equivalent to an increasing of the effectiveness of the switching mechanism.

Having a look at Fig. 3 at the pulse energies in the region around 1.2 m $< L <$ 1.3 m one can realize that they are still pretty low. One reason is that the effectiveness of the lens is modest at this resonator length as demonstrated in Fig. 10. But there is still another reason: at a resonator length of about $L = 1.25$ m the spot size w at the rod and consequently the initial beam truncation losses at the aperture of the rod are not large enough in order to store much pump energy in the laser crystal (Figs. 4 and 5). An increase of the initial losses can be accomplished by introducing an additional diaphragm in the vicinity of the rod with a smaller diameter than that of the rod. Doing this and decreasing the diameter of the aperture step by step the results demonstrated in Fig. 11 were obtained. As expected by the predictions presented in the previous section the effectiveness of the switching and therefore the pulse energies are increasing although the exploited rod volume is decreasing.

Repeating this experiment after locating the laser medium and the diaphragm close to the flat output coupler (see Fig. 12) should not provide a switching effect since appropriate to Fig. 9 in this case no reduction of the spot size takes place when assuming the build-up of a lens in

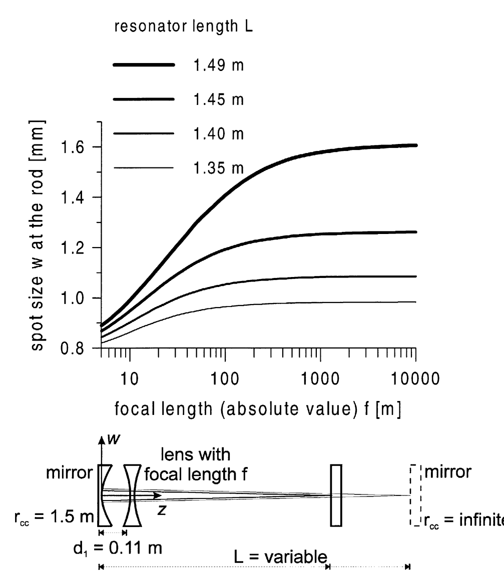

Fig. 10. Spot size of the fundamental mode at the rod versus focal length of the lens assumed in the rod for different resonator lengths L. Setup: lens close to the curved mirror, L variable.

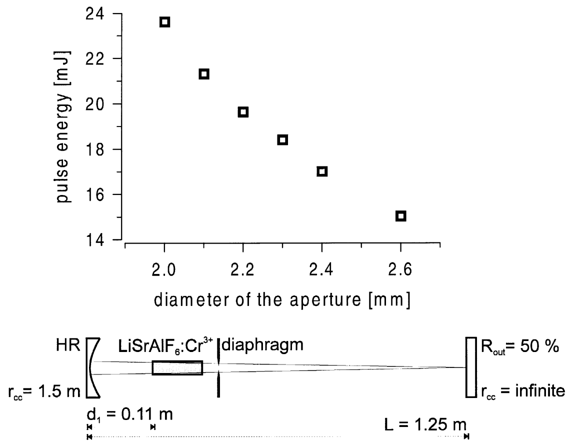

Fig. 11. Pulse energy versus the diameter of the aperture. Setup: rod and aperture close to the curved mirror, $L = 1.25$ m.

the rod and consequently no decrease of diffraction losses can be expected. As a matter of fact the experiment does not deliver growing pulse energies when reducing the diameter of the aperture.

Substituting in the setup of Fig. 11 the $LiSrAlF_6{:}Cr^{3+}$ rod by a Nd:YAG, Nd:YAP or Nd:glass rod, the same experiment does not deliver increasing pulse energies when decreasing the diameter of the aperture. This can be considered as evidence that the use of a crystal with a strong excited-state absorption within its emission band is an indispensable necessity for working of the described form of *Q*-switching.

In another experiment the supplementary diaphragm in Fig. 11 is replaced by a thin plate of fused silica, that means the beam truncation losses are substituted by reflection losses. Starting from Brewster's angle ($\beta_B \approx 55°$) and increasing the angle β and therefore the reflection losses step by step we measured the pulse energies. The results

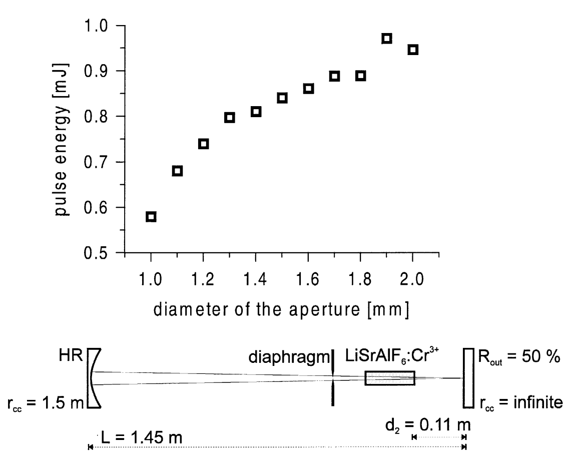

Fig. 12. Pulse energy versus the diameter of the aperture. Setup: rod and aperture close to the flat mirror, $L = 1.45$ m.

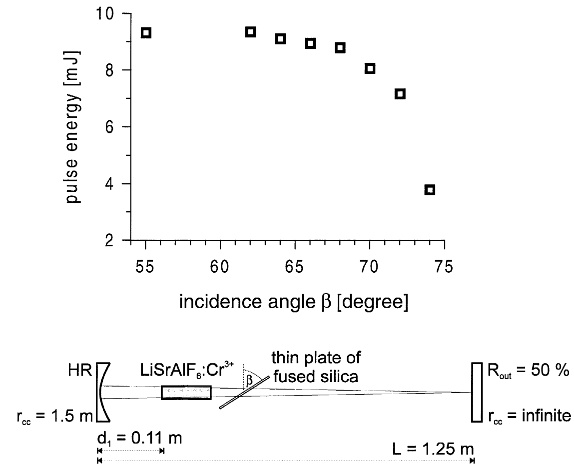

Fig. 13. Pulse energy versus angle of the thin plate of fused silica. Setup: aperture of Fig. 11 is substituted by a thin plate of fused silica.

are demonstrated in Fig. 13. Increasing the reflection losses allows an increased storage of pump energy in the crystal. But the initially high reflection losses cannot be diminished by the negative lens which is generated in the rod by the laser pulse and therefore no *Q*-switching can take place. Comparing this experiment with that in Fig. 11 this can be regarded as another proof that the development of a negative lens and the resulting reduction of losses at an aperture represent basic requirements of the presented switching mechanism.

6. Discussion of other potential causes responsible for the *Q*-switching

Other potential causes have to be envisaged and discussed.

One point to think about is the hypotheses that $LiSrAlF_6{:}Cr^{3+}$ operates as saturable absorber; but there is no ground-state absorption at the wavelength of $\lambda = 830$ nm and in Ref. [1] it was demonstrated that the ESA transition of Cr^{3+} cannot be saturated. The saturation of transitions of other particles (e.g. color centers or Cr^{4+} which possibly are created by any process, e.g. during the generation of the crystal) starting from an excited-state would be imaginable but there is no rational explanation then why this should depend on the existence of beam truncation losses and should not work when generating reflection losses instead (compare Fig. 11 and Fig. 12).

In Ref. [1] we thought about a Kerr lens *Q*-switching since the effect of reducing losses at an aperture by the build-up of a Kerr lens in the laser medium is a well known technique when realizing the so-called Kerr lens mode locking. But there are two reasons why this cannot work in the oscillator presented here. On the one hand the intensities created in this oscillator in the rod are too low for a sufficiently strong change of the refractive index. And even when the resulting focal length of the lens would be small enough, the lens created by the Kerr effect in connection with a Gaussian beam profile of the laser pulse is a positive lens. Using the setup presented in Fig. 1 this would lead to a widening of the fundamental mode in the region of the laser crystal and therefore to an increase of the losses at the aperture. So far, no Q-switching would be practicable.

So, other potential causes can be excluded as switch for the Q-switching presented here.

7. Determination of the focal length of the lens

Up to now we have discussed the switching mechanism and the origin of the lens in the rod which is necessary for the presented form of Q-switching, but no information was given about the focal lengths obtained in the experiments. Actually, the determination of the focal length is not very easy for several reasons:

For example, the very comfortable measurement technique with a position sensitive detector (PSD) as described in Ref. [8] cannot be applied since the development of the lens here is connected to the development of the laser pulse building-up in a few hundred nanoseconds. A PSD with such a short rise time is not available.

Because of dispersion an exact determination is connected to the wavelength of $LiSrAlF_6$:Cr^{3+} (here: $\lambda = 830$ nm) that means using lasers for the lensing measurements emitting at other wavelengths normally delivers wrong results.

We were proceeding in the following way, knowing that on the one hand this can only be an estimation of the focal length but on the other hand an evidence that the lens originating from the process described above is able to cause a Q-switching in the introduced form since the decrease of the focal length is strong enough:

First, we determined the change of the refractive index caused by the population inversion density which is generated when pumping the laser rod with an energy of $E = 13.5$ J which is identical to the pump energy needed in order to generate the pulses at a resonator length of $L = 1.49$ m (this was the resonator length which delivered the largest energies). This technique is described in detail in Ref. [9]. Since no suitable signal laser at $\lambda = 830$ nm was available we used an argon laser at $\lambda = 514.5$ nm for the interferometric measurements. At this wavelength, the ground-state absorption of $LiSrAlF_6$:Cr^{3+} is negligible [10] but the excited-state absorption cross section is of the same order of magnitude as that at $\lambda = 830$ nm (compare Ref. [11] with Ref. [6] and Ref. [7]). So, the changes of the refractive index at the two wavelengths caused by changes of the inversion density cannot be expected to be identical but comparable. Of course, the population inversion generated by the pump pulse is not completely reduced by the laser pulse and consequently the reduction of the refractive index caused by the laser pulse at the rod axis for example is smaller than the change of refractive index determined in the way described above. By a computer simulation (this will not be described here) we determined this relation and obtained a change of the refractive index at the rod axis caused by the laser pulse of about $\Delta n = 2 \times 10^{-6}$. Assuming the laser pulse as shown in Fig. 8 and therefore assuming no change of refractive index at the rod edge and supposing for simplicity a quadratic refractive index profile across the rod cross section we can estimate the minimum focal length to about $f = -10$ m. Although this seems to be a long focal length, Fig. 6 shows that this causes a strong reduction of the spot size in the region of the laser rod using the setup of Fig. 1.

So far we demonstrated that this kind of lens is able to provide a refractive power which is strong enough to make possible the described form of Q-switching.

8. Summary

We report a new, simple, convenient, and cheap method of Q-switching which delivers pulse energies of 60 mJ and widths (FWHM) of 200 ns. The switching mechanism is explained and the requirements are listed. A series of experiments is provided confirming the presented switching theory, other possible causes are excluded.

References

[1] B.C. Weber, A. Hirth, Optics Comm. 128 (1996) 158.
[2] H.H. Zenzie, Y. Isyanova, Optics Lett. 20 (1995) 169.
[3] J.W. Pierce, R.G. Beausoleil, SPIE 2379 (1995) 43.
[4] T. Li, Bell Syst. Techn. J. (1965) 916.
[5] M. Born, E. Wolf, Principles of Optics, sixth ed., Pergamon Press, 1993.
[6] P. Beaud, M.C. Richardson, Y.-F. Chen, B.H.T. Chai, IEEE J. Quantum Electron. 30 (1994) 1259.
[7] W.R. Rapoport, Excited-state absorption and upconversion in Cr:LiSAF, in: OSA Proc. on Advanced Solid-State Lasers, 1992, Vol. 13, pp. 21–27.
[8] R. Paugstadt, M. Bass, Appl. Optics 33 (1994) 954.
[9] K.F. Wall, R.L. Aggarwal, M.D. Sciacca, H.J. Zeiger, R.E. Fahey, A.J. Strauss, Optics Lett. 14 (1989) 180.
[10] S.A. Payne, L.L. Chase, L.K. Smith, W.L. Kway, H.W. Newkirk, J. Appl. Phys. 66 (1989) 1051.
[11] J.J. Kim, C.-M. Kim, J. Scheid, B.H.T. Chai, Cr^{3+}:$LiSrAlF_6$ laser pumped by a pulsed dye laser, in: OSA Proc. on Advanced Solid-State Lasers, 1992, Vol. 13, pp. 5–9.