

Passive Q switching of the alexandrite laser with a Cr⁴⁺:Y₂SiO₅ solid-state saturable absorber

Yen-Kuang Kuo and Milton Birnbaum

University of Southern California, Center for Laser Studies, University Park, DRB 17, Los Angeles, California 90089-1112

(Received 16 March 1995; accepted for publication 26 April 1995)

Passive Q switching of a flashlamp-pumped alexandrite laser with a Cr⁴⁺:Y₂SiO₅ (Cr⁴⁺:YSO) solid-state saturable absorber has been demonstrated at room temperature. An output of a single Q-switched laser pulse of 20 mJ in energy and 70 ns in duration was obtained. The output wavelength of the Q-switched laser pulse and the free-running laser was 753 nm. © 1995 American Institute of Physics.

Passive Q switching of solid-state lasers with solid state saturable absorbers have received much attention in the past few years and several solid-state passive Q switches have been developed for the solid-state lasers operating at various wavelengths (see, for examples, Refs. 1–10). In prior work¹⁰ we showed that Cr⁴⁺:Y₂SiO₅ (Cr⁴⁺:YSO) worked efficiently as a solid-state saturable absorber Q-switch for the Cr:LiCaAlF₆ (Cr:LiCAF) laser operating near 780 nm. In this letter, we report the passive Q switching of the Cr³⁺:BeAl₂O₄ (alexandrite) laser with the Cr⁴⁺:YSO saturable absorber operated near 750 nm.

Alexandrite laser,^{11–13} which is tunable at least from 700 to 818 nm, has a low threshold and high slope efficiency. The alexandrite crystal has broad absorption bands peaking near 420 and 580 nm, which are assigned to the ⁴A₂→⁴T₁ and ⁴A₂→⁴T₂ absorption transitions, respectively. The broad visible absorption bands in alexandrite and the long fluorescence lifetime of about 260 μs at room temperature are of advantage for both flashlamp pumping and Q-switched operation.

Alexandrite, which is biaxial with emitted light polarized parallel to the *b* axis, can act either as a three-level laser system or as a four-level vibronic laser system. As a three-level system, laser action occurs on the R₁ line (²E→⁴A₂) at 680.4 nm. When operated as a four-level vibronic system laser transition starts from ⁴T₂ and ends at the ⁴A₂ multiplets; the ²E serves as the energy storage level. There is coupling between ²E and ⁴T₂ because of their small energy difference (ΔE≈800 cm⁻¹). The peak wavelength of the alexandrite laser without a tuning element is ~750 nm. The effective emission cross section is about 7×10⁻²¹ cm² at room temperature, which is close to that of the Cr:LiCaAlF₆ laser.

The polarized absorption spectra of the Cr⁴⁺:YSO saturable absorber, measured using a Varian Cary spectrophotometer at room temperature, is shown in Fig. 1. The broad absorption band of the Cr⁴⁺:YSO crystal near 750 nm, which is assigned to the ³A₂→³T₁ absorption transitions,¹⁴ indicates potential application as a saturable absorber Q switch for the alexandrite laser. The emission lifetime of the Cr⁴⁺:YSO saturable absorber used in this passive Q-switching experiment is 0.7 μs at room temperature.¹⁰

The criterion for saturable absorber Q switching of a four-level vibronic laser system is⁷

$$\frac{\sigma_a}{\sigma_g} \times \frac{A_g}{A_a} > 1, \quad (1)$$

where σ_a is the ground state absorption cross section of the saturable absorber, σ_g is the emission cross section of the laser, A_g is the effective laser beam area on laser rod, and A_a is the effective laser beam area on saturable absorber. The ground state absorption cross section of the Cr⁴⁺:YSO saturable absorber is about 7×10⁻¹⁹ cm² at 694 nm with polarization of the incident laser beam parallel to the *n*₃ axis and propagation along the *n*₂ axis.¹⁰ Figure 2 shows the ground state absorption cross section of the Cr⁴⁺:YSO saturable absorber near 750 nm. Cr⁴⁺:YSO has an absorption cross section of 7.2×10⁻¹⁹ cm² at 750 nm which is substantially greater than the emission cross section of the alexandrite laser (7×10⁻²¹ cm²) at the same wavelength. Since the absorption cross section of the Cr⁴⁺:YSO crystal is much greater than the emission cross section of the alexandrite laser over its entire tuning range, according to the passive Q-switching criterion [Eq. (1)], Cr⁴⁺:YSO can be used as a saturable absorber Q switch for the alexandrite laser without intracavity focusing.

Passive Q switching of the alexandrite laser with Cr⁴⁺:YSO was demonstrated using a 30-cm-long laser resonator consisting of a flat high reflector and a flat output coupler. The experimental arrangement is shown in Fig. 3(a) and the reflectivity spectra of the high reflector and output coupler are shown in Fig. 3(b). The 4-in.-long alexandrite laser

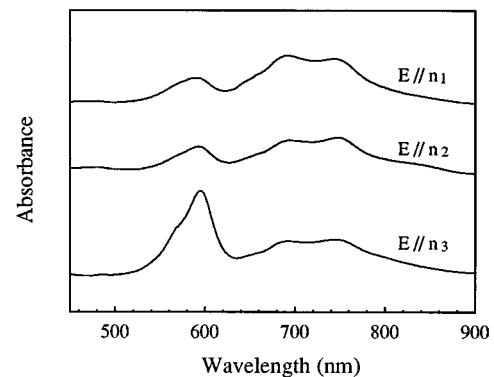


FIG. 1. Polarized absorption spectra of the Cr⁴⁺:YSO saturable absorber measured at room temperature.

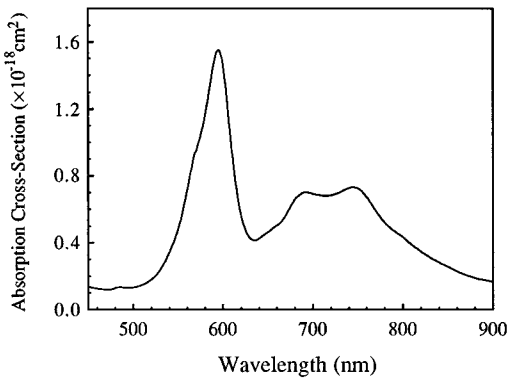


FIG. 2. Absorption cross section of the Cr^{4+} :YSO saturable absorber with polarization parallel to the n_3 axis and propagation along the n_2 axis (Ref. 10).

rod and the 1.5-mm-thick Cr^{4+} :YSO saturable absorber were polished flat-flat and were uncoated. Owing to the structure of the laser rod enclosure, only 8 cm of the laser rod was exposed to the pump light from the xenon flashlamp. At a flashlamp input energy of 64 J, a single Q -switched laser pulse was observed. Figure 4 shows the temporal profile of the Q -switched laser pulse which was recorded with a fast silicon detector of less than 1 ns rise time and a Tektronix TDS 540 digitizing oscilloscope of 500 MHz bandwidth.

The energy of the Q -switched laser pulse, measured using a Scientech 365 calorimeter, was ~ 20 mJ and the pulse duration (full width at half-maximum) was about 70 ns. The wavelength of the Q -switched laser pulse, measured with an optical multiple-channel analyzer (OMA), was 753 nm

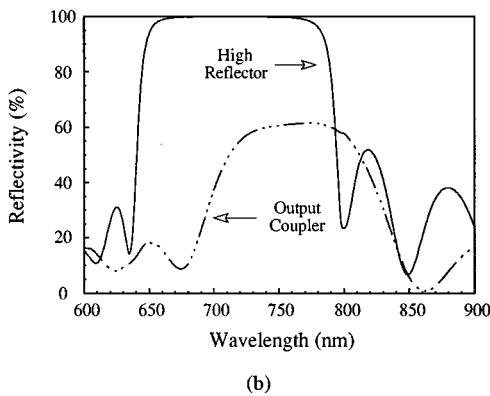
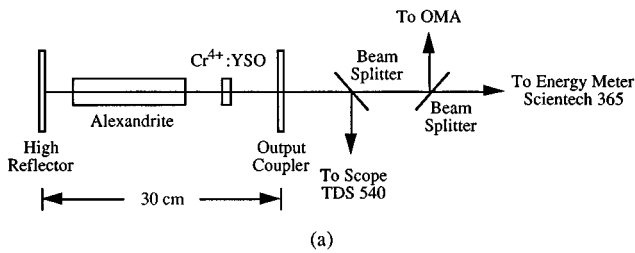


FIG. 3. (a) Experimental setup for the alexandrite passive Q switching with Cr^{4+} :YSO saturable absorber (b) reflectivity spectra of the high reflector and output coupler.

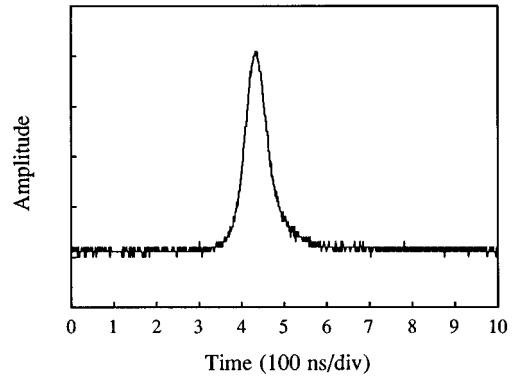


FIG. 4. Temporal profile of the Q -switched alexandrite laser pulse.

which was the same as that of the alexandrite free-running laser output. The free-running laser pulse had a spectral width of about 2.5 nm and a laser beam diameter of about 2.3 mm while the Q -switched laser pulse had a spectral width of about 2 nm and a laser beam diameter of about 1.8 mm.

When the Cr^{4+} :YSO saturable absorber was removed the free-running energy of the alexandrite laser was about 80 mJ at 64 J flashlamp input energy. The Q -switching efficiency, defined as the ratio of the Q -switched laser output energy to the free-running energy at the same pumping level, was about 25%. If spatial aperturing is taken into account, the Q -switching efficiency was about 40%.

Following the method of Siegman,¹⁵ the rate equations describing the passive Q switching of the alexandrite laser with Cr^{4+} :YSO saturable absorber can be written⁷

$$\frac{dn}{dt} = [K_g N_g - K_a N_a - \beta K_a (N_{a0} - N_a) - \gamma_c] n, \quad (2)$$

$$\frac{dN_g}{dt} = R_p - \gamma_g N_g - K_g N_g n, \quad (3)$$

$$\frac{dN_a}{dt} = \gamma_a (N_{a0} - N_a) - K_a N_a n. \quad (4)$$

The parameters used in these coupled rate equations are defined as follows: n is the photon number in the laser cavity, N_g is the population inversion of the laser, N_a is the ground state population of the saturable absorber; N_{a0} is the initial value of N_a ; γ_g is the decay rate of the upper laser level; γ_a is the relaxation rate of the saturable absorber; R_p is the pumping rate; γ_c is the cavity decay rate; K_g and K_a are coupling coefficients; and $\beta = \sigma_{\text{ESA}} / \sigma_a$ is the ratio of the excited state absorption cross section σ_{ESA} , to the ground state absorption cross section σ_a , of the saturable absorber. A normalized loss factor can be defined from Eq. (2) as

$$\text{loss} = \frac{K_a N_a + \beta K_a (N_{a0} - N_a) + \gamma_c}{K_g}. \quad (5)$$

Equations (2)–(4) were numerically solved to investigate the behavior of alexandrite passive Q -switching with Cr^{4+} :YSO saturable absorber. As shown in Fig. 5, the loss decreases when the photon number inside the laser cavity increases due to the bleaching effect of the Cr^{4+} :YSO satu-

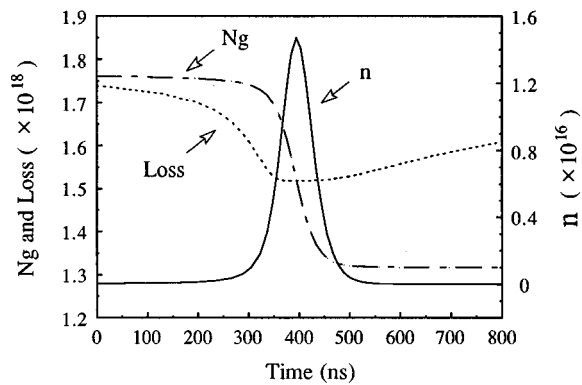


FIG. 5. Results of the numerical simulation: n , N_g , and loss as a function of time.

rable absorber. According to Fig. 5, the loss reaches its minimum value early in the development of the Q -switched pulse. This is characteristic of an efficient saturable absorber Q switch and is the result of a favorable cross-section ratio and a lifetime of the upper state of the saturable absorber which is much longer than the duration of the Q -switched pulse. The increase of the loss after the release of the Q -switched laser pulse is due to the relaxation of the saturable absorber population.

In conclusion, the $\text{Cr}^{4+}:\text{YSO}$ crystal has been demonstrated to be an effective solid-state saturable absorber for the alexandrite laser at 753 nm. A single Q -switched laser pulse of 20 mJ and 70 ns was obtained. The Q -switching efficiency is 25%. If the spatial aperturing is taken into account the Q -switching efficiency is about 40%.

The authors wish to thank William R. Rapoport of the Allied Signal Inc., Morristown, NJ, for the alexandrite laser rod and mirrors, A. V. Shestakov of the Russian Academy of Science for the $\text{Cr}^{4+}:\text{YSO}$ crystal, and Man-Fang Huang of the Center for Laser Studies, University of Southern California, for the experiment assistance.

- ¹D. M. Andrauskas and C. Kennedy, *Proceedings of Advanced Solid-State Lasers* (Optical Society of America, Washington, DC, 1991), p. 393.
- ²I. J. Miller, A. J. Alcock, and J. E. Bernard, *Proceedings of Advanced Solid-State Lasers* (Optical Society of America, Washington, DC, 1992), p. 322.
- ³M. I. Demchuk, V. P. Mikhailov, N. I. Zhavoronkov, N. V. Kuleshov, P. V. Prokoshin, K. V. Yumashev, M. G. Livshits, and B. I. Minkov, *Opt. Lett.* **17**, 929 (1992).
- ⁴V. P. Mikhailov, N. V. Kuleshov, N. I. Zhavoronkov, P. V. Prokoshin, K. V. Yumashev, and V. A. Sandulenko, *Opt. Mater.* **2**, 267 (1993).
- ⁵K. Spariosu, R. D. Stultz, M. Birnbaum, T. H. Allik, and J. A. Hutchinson, *Appl. Phys. Lett.* **62**, 2763 (1993).
- ⁶R. D. Stultz, M. B. Camargo, S. T. Montgomery, M. Birnbaum, and K. Spariosu, *Appl. Phys. Lett.* **64**, 948 (1994).
- ⁷Y. K. Kuo, W. Chen, R. D. Stultz, and M. Birnbaum, *Appl. Opt.* **33**, 6348 (1994).
- ⁸Y. K. Kuo, M. Birnbaum, and W. Chen, *Appl. Phys. Lett.* **65**, 3060 (1994).
- ⁹M. B. Camargo, R. D. Stultz, M. Birnbaum, and M. Kokta, *Opt. Lett.* **20**, 339 (1995).
- ¹⁰Y. K. Kuo, M. F. Huang, and M. Birnbaum, *IEEE J. Quantum Electron.* **QE-31**, 657 (1995).
- ¹¹J. C. Walling, O. G. Peterson, H. P. Jenssen, R. C. Morris, and E. W. O'Dell, *IEEE J. Quantum Electron.* **QE-16**, 1302 (1980).
- ¹²J. C. Walling, D. F. Heller, H. Samelson, D. J. Harter, J. A. Pete, and R. C. Morris, *IEEE J. Quantum Electron.* **QE-21**, 1568 (1985).
- ¹³W. Koechner, *Solid State Laser Engineering*, 3rd ed. (Springer-Verlag, Berlin, 1992).
- ¹⁴U. Hömmerich, H. Eilers, S. M. Jacobsen, W. M. Yen, and W. Jia, *J. Lumin.* **55**, 293 (1993).
- ¹⁵A. E. Siegman, *Lasers* (University Science Books, Mill Valley, CA, 1986).