Co^{2+}:YSGG saturable absorber *Q* switch for infrared erbium lasers

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Passive *Q* switching of Er:glass (1.53 μm) with a new, robust, solid-state saturable absorber, Co^{2+}:$Y_3Sc_2Ga_3O_{12}$, has been demonstrated. *Q*-switched pulses of 20 ns and 4 mJ of energy were obtained. An absorption cross section of 5×10^{-20} cm^2 was measured. Preliminary results for a Co^{2+}:$Y_3Al_5O_{12}$ saturable absorber *Q* switch are also discussed.

We have shown that the 1.5-μm Er:glass laser can be passively *Q* switched by use of Er^{3+}:$Ca_5(PO_4)_3F$,[1] U^{4+}:SrF_2,[2] and Er^{3+}:CaF_2.[3] This previous work indicated the need for more robust (higher-damage threshold) host materials for saturable absorber *Q* switches at 1.5 μm. Co^{2+}:$Y_3Sc_2Ga_3O_{12}$ (Co^{2+}:YSGG) provides a higher damage threshold than obtained with other 1.5-μm saturable absorber *Q* switches, and, in addition, a shorter *Q*-switched pulse (20 ns) was obtained.

Co^{2+}, in materials such as MgF_2 (Refs. 4 and 5) and $KZnF_3$,[6] has been used as a tunable laser source from 1.5 to 2.3 μm. Like other transition-metal-ion-doped crystals, Co^{2+}:YSGG possesses broad absorption bands, including one from 0.9 to 1.8 μm (Fig. 1). The absorption spectra for Co^{2+}:YSGG and Co^{2+}:$Y_3Al_5O_{12}$ (Co^{2+}:YAG) were measured at room temperature with a Cary 2415 spectrophotometer. It is expected that Co^{2+} will substitute only for the scandium (octahedral site symmetry)[7] ion in YSGG. Thus the energy-level transition at 1.5 μm for the Co^{2+} ion in YSGG (octahedral symmetry) would be $^4T_1 \rightarrow {}^4T_2$.[8] The Co^{2+}:YAG absorption spectrum presents a similar absorption band but shifted to shorter wavelengths, indicative of a stronger crystal field (Fig. 1). The broad absorption bands of Co^{2+}:YSGG and Co^{2+}:YAG indicate that they could provide saturable absorber *Q* switches for lasers such as Tm^{3+}:YLF (1.45 μm) and Er^{3+}:YAG (1.64 μm) for which passive *Q* switches are not available.

The Co^{2+}:YSGG crystal used in this work was grown by the standard Czochralski method. The stoichiometric melt (1400 g charge) was placed in a 3 in. $\times$ 3 in. (7.6 cm $\times$ 7.6 cm) crucible with an atmosphere of N_2 plus 1500 parts in 10^6 O_2. The growth rate was 1 mm/h, and the rotation rate was 10 rpm. The crystal boule was 1.3 in. (3.3 cm) in diameter and 6 in. (15.2 cm) long, grown along the ⟨111⟩ direction (a seed of undoped ⟨111⟩ YSGG was used). The cobalt concentration was 2% at. wt., and silicon was added to the melt for charge compensation.

The saturation fluence of the Co:YSGG was measured with a Raman-shifted Nd:YAG laser at 1543 nm, which is very close to the Er:glass laser wavelength of 1532 nm (Fig. 1). The 1543-nm light (linearly polarized) was focused to approximately a 0.5-mm spot diameter (e^{-2} point) with a FWHM pulse width of 15 nsec and a FWHM spectral bandwidth of less than 1 nm. The Co:YSGG crystal used in the bleaching experiment was 1 cm thick with a 1.54-μm internal small-signal transmittance of 3.7%. The 1.54-μm beam axis was aligned normal to the crystal surfaces (parallel to the ⟨111⟩ crystallographic direction). The results of this experiment are shown in Fig. 2(a). Rotating the 1.54-μm input polarization about the ⟨111⟩ axis did not alter the bleaching results shown in Fig. 2(a). A 0.81-cm-thick Co^{2+}:YAG crystal was tested in the same way [Fig. 2(b)]; however, Co:YAG suffered optical damage at an incident fluence of only 2.5 J/cm^2, whereas with the Co:YSGG crystal no damage was observed, even at the highest level of 8 J/cm^2. The Co:YAG results are preliminary, and we anticipate that higher damage threshold crystals can be grown.

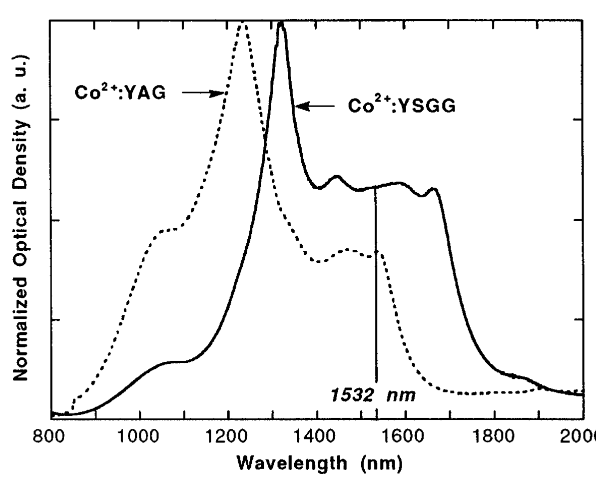

Fig. 1. Absorption spectra of Co^{2+}:YSGG and Co^{2+}:YAG near 1.5 μm.

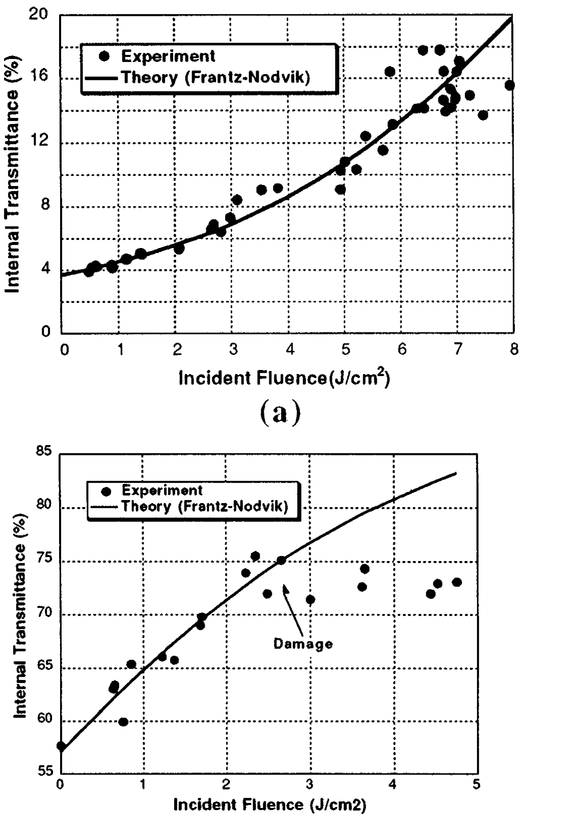

Fig. 2. Bleaching data at 1543 nm of (a) Co^{2+}:YSGG and (b) Co^{2+}:YAG.

The transmittance data were modeled by using the modified Frantz–Nodvik formula.[9] This formula is valid for the case of a slowly relaxing saturable absorber with negligible excited-state absorption and is given by

$$T = \frac{e_s}{e_i} \ln\left\{\left[\exp(e_i/e_s) - 1\right]T_0 + 1\right\}, \tag{1}$$

where T is the saturated transmittance, e_i is the incident fluence, e_s is the saturation fluence ($= h\nu/\sigma_{\text{eff}}$), and T_0 is the small-signal transmittance. A least-squares fit of the Co:YSGG experimental transmittance data [Fig. 2(a)] by use of Eq. (1) yielded a value of $e_s = 2.48$ J/cm^2, which corresponds to $\sigma_{\text{eff}} = 5.2 \times 10^{-20}$ cm^2. A similar analysis of the Co:YAG data [Fig. 2(b)], for fluences up to the onset of damage, gave a value of 1.5 J/cm^2 for the saturation fluence and $\sigma_{\text{eff}} = 8.6 \times 10^{-20}$ cm^2.

The Q-switching results for Co:YSGG were obtained using a Kigre 4 mm × 76 mm QE-7S Er:glass rod. The rod was pumped with a flashlamp pulse of ~600 μs FWHM. The pump cavity used in this experiment was designed for a much larger laser rod and therefore was not an optimized system. The threshold with the Q switch inserted in the cavity was approximately 40 J, and the threshold for the free-running laser (i.e., after removal of the Q switch) was 27 J. The resonator cavity consisted of one flat and one curved mirror, separated by 23.5 cm (Fig. 3). An intracavity +5-cm focal-length lens was used to concentrate the light in the Q switch. The outcoupler had a curvature of 2.5 cm and a reflectivity of 94% at the laser wavelength. The other resonator mirror was flat and 100% reflective. This configuration is a stable resonator that forms a beam waist between the lens and the curved mirror.

The Q-switch crystal was 0.5 mm thick, uncoated, with parallel faces, and had an internal transmittance of 85% (corresponding to an absorption coefficient of 3.25 cm^{-1} at 1532 nm). The polished surfaces, aligned parallel to the resonator cavity mirrors, were perpendicular to the crystallographic direction ⟨111⟩. The Q switch was positioned near the intracavity beam waist (Fig. 3).

A typical output pulse of the Co:YSGG Q-switched laser (4 mJ, 20 ns) is shown in Fig. 4 and was recorded with an InGaAs diode detector and a Tektronix TDS540 digital oscilloscope. Energy measurements were made with a Scientech 365 calorimeter. The wavelength of the Q-switched output (1532 nm) was measured using a 0.25-m Jarrell-Ash monochromator. This was near the peak of the Er:glass luminescence but ~2 nm shorter than that obtained for the free-running laser (1534 nm).

The 4-mJ Q-switched output energy was approximately 13% of the free-running output (i.e., with Q switch removed) at the same flashlamp input energy. However, the Q switch was used uncoated, and thus the Fresnel normal-incidence surface reflection losses must be taken into account. For YSGG these (single-pass) losses are ~16%. We estimated

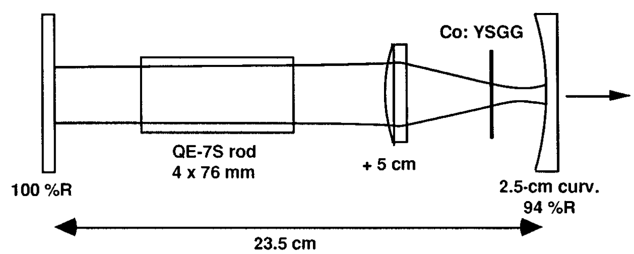

Fig. 3. Resonator cavity used for the Q-switching experiment.

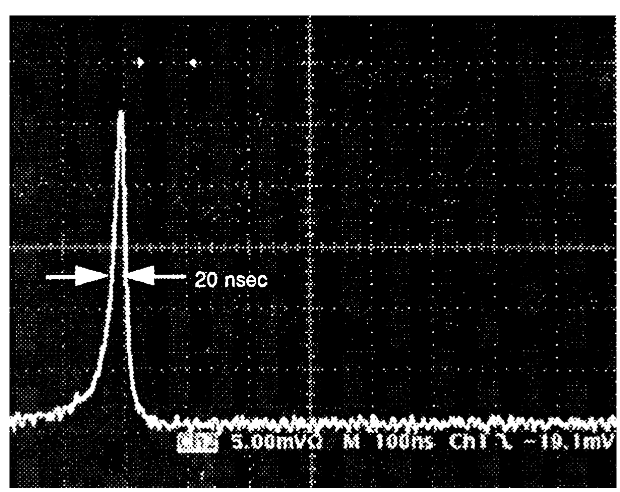

Fig. 4. Er:glass output pulse (20 ns FWHM) with the Co^{2+}:YSGG Q switch.

the efficiency in Q-switched operation by using the following equation[10]:

$$\eta_c = \frac{T}{T + L}, \tag{2}$$

where T is the transmittance of the output mirror and L is the round-trip resonator-cavity loss. For our laser, $T = 6\%$ and $L = 32\%$ (double-pass losses), and therefore $\eta_c \approx 16\%$ from Eq. (2). Thus the Q-switched energy efficiency was ~80% (0.13/0.16) that of the free-running laser.

Co:YAG was also tested as a Q switch, and the shortest pulse obtained was 88 ns FWHM and had an output energy of less than 1 mJ. However, the Co:YAG crystal was damaged when we attempted to obtain shorter pulses by increasing the focusing in the crystal. Only a single Co:YAG sample was available, and attempts to obtain Co:YAG with improved damage resistance are in progress.

The rate equations for the case of a slowly relaxing saturable absorber Q switch with a three-level laser are given by Szabo and Stein[11] and by Siegman[12]:

$$\frac{d\phi}{dt} = (K_g N_g - K_a N_a - \gamma_c)\phi, \tag{3}$$

$$\frac{dN_g}{dt} = -\gamma K_g N_g \phi, \tag{4}$$

$$\frac{dN_a}{dt} = -K_a N_a \phi, \tag{5}$$

where ϕ is the number of photons in the cavity, γ_c is the photon-cavity decay rate excluding the saturable loss, and N_g and N_a are the gain and absorber media population differences. $\gamma = 1 + g_2/g_1$, where g_2 and g_1 are the upper and lower laser level degeneracies for the laser-active material, respectively. It was assumed that $g_1 = g_2$, or $\gamma = 2$, for Er:glass. The coupling coefficients K_i are given by $K_i = \sigma_i/t_1 A_i$, where $\sigma_{g,a}$ are the gain and absorber media cross sections and t_1 is the one-way photon-cavity transit time.

Computer solutions of Eq. (3)–(5) with cross sections of 0.8×10^{-20} and 5.2×10^{-20} cm^2, respectively, for the Er:glass[13] and Co:YSGG indicated that Q switching should occur without intracavity focusing; however, we observed only free-running (non-Q-switched) pulses when the light was not focused into the Q switch. This discrepancy may be due to a short relaxation lifetime that was not accounted for in the slowly relaxing model.

When focusing was introduced in the theory a simulated pulse width of 29 ns was obtained, in good agreement with the experimental value of 20 ns. The predicted pulse shape was in agreement with that observed experimentally (Fig. 4).

In conclusion, a new passive Q switch for the eye-safe Er:glass laser was demonstrated. Q-switched pulses of 20-ns duration were obtained. We anticipate that this new saturable absorber Q switch will permit high repetition rates with short pulse durations and could extend the operating range of eye-safe Q-switched Er:glass lasers.

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References

1. K. Spariousu, R. D. Stultz, M. Birnbaum, T. H. Allik, and J. A. Hutchinson, Appl. Phys. Lett. **62,** 2763 (1993).
2. R. D. Stultz, M. B. Camargo, S. T. Montgomery, M. Birnbaum, and K. Spariousu, Appl. Phys. Lett. **64,** 948 (1994).
3. M. B. Camargo, R. D. Stultz, M. Birnbaum, and K. Spariosu, in *Conference on Lasers and Electro-Optics,* Vol. 8 of 1994 OSA Technical Digest Series (Optical Society of America, Washington, D.C., 1994), paper CtuK53, p. 115.
4. P. F. Moulton, IEEE J. Quantum Electron. **QE-21,** 1582 (1985).
5. D. Welford and P. F. Moulton, Opt. Lett. **13,** 975 (1988).
6. W. Kunzel, W. Knierim, and U. Dürr, Opt. Commun. **36,** 383 (1981).
7. A. A. Kaminskii, *Laser Crystals* (Springer-Verlag, New York, 1981), Chap. 9, p. 262.
8. P. F. Moulton, in *Laser Handbook,* M. Bass and M. L. Stitch, eds. (North-Holland, Amsterdam, 1985), Vol. 5, pp. 265–269.
9. L. Frantz and J. Nodvik, J. Appl. Phys. **34,** 2346 (1963).
10. W. Koechner, *Solid-State Laser Engineering,* 3rd ed. (Springer-Verlag, New York, 1992), Chap. 3, p. 93.
11. A. Szabo and R. A. Stein, J. Appl. Phys. **36,** 1562 (1965).
12. A. Siegman, *Lasers* (University Science, Mill Valley, Calif., 1986), Chap. 26.
13. S. J. Hamlin, J. D. Myers, and M. J. Myers, Proc. Soc. Photo-Opt. Instrum. Eng. **1419,** 100 (1991).