Passive Q-switching of the Erbium:Glass Laser Using $Er^{3+}:CaF_2$

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Eyesafe Er:glass lasers (1.54 μm) are interesting and useful for a large number of applications such as communications, optical atmospheric studies, traffic enforcement, obstacle avoidance, and air defense.[1-4] Many applications require short 1.5 μm pulses with high peak power which can be obtained by Q-switching the Er:glass laser. A saturable absorber Q-switch is the simplest and least expensive Q-switch option, also permitting a very compact resonator size.

Er:glass is a three-level laser where the 1.54 μm transition, $^4I_{13/2} \rightarrow {}^4I_{15/2}$, terminates in the ground-state. Consequently, many Er-doped materials may be used as saturable absorber Q-switches because of the significant overlap of the Er^{3+}:host absorption spectra with the Er:glass emission spectrum.

Er:CaF_2 possesses a broad, continuous absorption spectra nearly coincident with the emission spectrum of the Er:glass (Fig. 1). The shorter effective relaxation lifetime of Er:CaF_2 avoids the free-running problems encountered with other Er-doped crystal Q-switches, such as $Er^{3+}:Ca_5(PO_4)_3F$ (or Er:FAP).[5] The Er:CaF_2 crystals used in these experiments, with 2.0 and 3.5% of Er, were obtained from Optovac, Inc.

Undoped CaF_2 crystals have the cubic structure of fluorite with space group Fm3m.[6] The divalent cations (Ca^{2+}) are at (0,0,0) with the fluorine ions at ±(1/4,1/4,1/4) in an FCC lattice. The presence of Er^{3+}, which replaces the Ca^{2+} ion, distorts the otherwise cubic symmetry due to several possible charge compensation mechanisms, i.e. multiple sites with various crystalline field symmetries are possible. As a result, the optical spectra of Er^{3+} in CaF_2 are complex and characterized by the presence of a large number of overlapping inhomogeneously broadened electronic and/or vibronic lines. The broad (full width at half maximum ≈ 66 nm) absorption band of our (3.5%)Er:CaF_2 crystal with the maximum around 1.54 μm is shown in Fig. 1, along with Er:glass (Kigre QE-7) fluorescence. The absorption spectrum for the (2%)Er:CaF_2 was the same, except the peak absorption coefficient was 2.7 cm^{-1}, instead of 4.4 cm^{-1}.

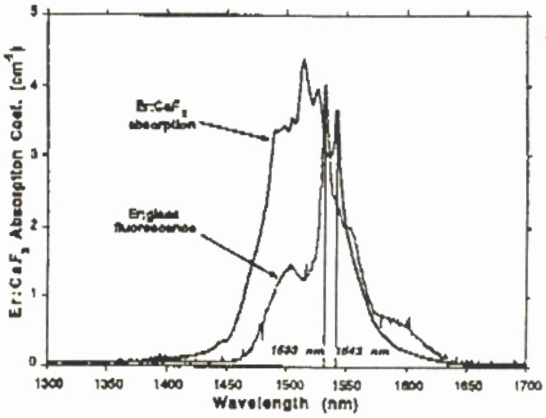

Figure 1. (3.5%)Er:CaF_2 absorption and Er:glass fluorescence.

An Er:glass laser, passively Q-switched with a $U^{2+}:SrF_2$ saturable absorber Q-switch,[7] was used as the excitation source for the lifetime experiments. The laser output energy was 5 mJ and the pulsewidth was 138 ns, full width at half maximum (FWHM). This Q-switched laser had a wavelength of 1533 nm. The Er-crystals were placed near the focus of a +15 cm focal length lens, used to concentrate the laser beam into a 400 μm spot and produce an incident fluence of about 4 J/cm^2.

The crystal fluorescence (Fig. 2) was collected using a fast (f/1.2) glass lens. The light signal was detected by a Ge photodiode (Judson, J16-series). A thin silicon crystal was placed in front of the Ge

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diode to block possible emissions associated with Er^{3+} energy levels higher than $^4I_{13/2}$.

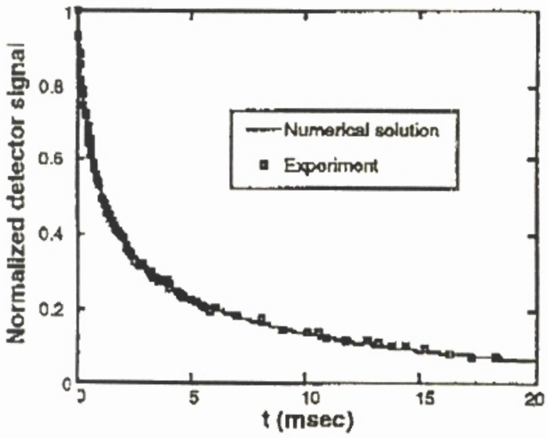

Figure 2. (3.5%)$Er:CaF_2$ fluorescence.

Multi-ion processes are strong in $Er:CaF_2$, typically resulting in highly nonexponential $^4I_{13/2}$ fluorescence decays, even with relatively low Er concentrations. An attempt to model the observed decay rates in terms of pair theory[8] proved unsuccessful. Instead, we used the following rate equation for the Er^{3+} $^4I_{13/2}$ population density (m), which includes both quadratic and cubic terms:

$$\frac{dm}{dt} = -\alpha_1 m - \alpha_2 m^2 - \alpha_3 m^3 \qquad (1)$$

Using the method of partial fractions, equation (1) can be put in the following closed transcendental form:

$$\mu\left(\frac{1+a\mu}{1+a}\right)^{\frac{a}{b-a}}\left(\frac{1+b\mu}{1+b}\right)^{\frac{b}{a-b}} = e^{-\alpha_1 t} \qquad (2)$$

where $\mu \equiv m/m_0$, m_0 is the initial ($t = 0$) value of m, and a, b are defined by:

$$a \equiv \frac{F_1 + [F_1^2 - 4F_2\alpha_1]^{0.5}}{2\alpha_1} \qquad b \equiv \frac{F_1 - [F_1^2 - 4F_2\alpha_1]^{0.5}}{2\alpha_1} \qquad (3)$$

where $F_1 \equiv \alpha_2 m_0$, $F_2 \equiv \alpha_3 m_0^2$. We numerically solved equation (2), and adjusted the parameters a, b, and α_1 to yield the best fit to the measured $Er:CaF_2$ fluorescence (solid curve in Fig. 2). When Q-switching, the faster decay near the excitation time ($t = 0$) is important. With the (2%)$Er:CaF_2$ crystal, the initial (effective) lifetime was about 45 μs, whereas the slower (exponential) component was over 12 ms.

The absorption cross-section for $Er:CaF_2$ was obtained by bleaching the 2% crystal with a short pulse (14 ns, FWHM) of 1543 nm light from a Raman-shifted Nd:YAG laser, with a spectral linewidth of less than 1 nm. The measured Frantz-Nodvik saturation fluence ($h\nu/\sigma_{eff}$) yielded an effective absorption cross section (σ_{eff}) of 1.43 x 10^{-20} cm^2.

Two $Er:CaF_2$ samples were used to perform the Q-switch experiments: a) 1.0 mm thick piece with 2.0% Er concentration, and b) a 1.1 mm thick piece with 3.5% Er concentration. Both switches were cut and polished with flat and parallel surfaces, and were used uncoated. Since the $Er:CaF_2$ absorption cross-section value is comparable to that of glass, intracavity focusing was necessary to obtain Q-switching.[5]

The Q-switched resonator cavities, both of which possessed stable Gaussian modes, are shown in Fig. 3. The cavity shown in Fig. 3a was flat-flat and with mirror reflectivities of 100% and 88% (outcoupler), at 1533 nm. The length was 21 cm, and a +7.6 cm lens was used to focus the laser beam into the Q-switch. The output mirror in Fig. 3b had a 94% (1533 nm) reflectivity, with a 2.5 cm radius of curvature. The cavity length in this case was 17.5 cm, and a +5 cm intracavity lens was used. All the resonator internal components (except the Q-switches) were AR-coated at 1.54 μm. The Q-switches were always positioned between the output mirror and the intracavity lens, close to the Gaussian beam waist.

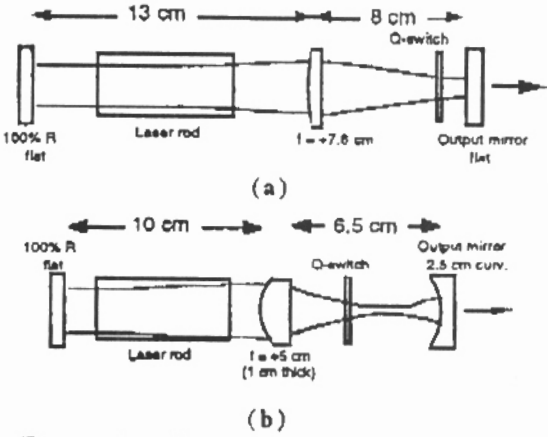

Figure 3. Er:glass resonator cavities.

The Er:CaF$_2$ Q-switch results were obtained using a QE-7S, 3 x 50 mm Er:glass rod, pumped by a Xenon flashlamp with a FWHM pulsewidth of approximately 600 µs. The free-running laser had a threshold of about 14 J with an output slope efficiency of 0.51% for the cavity in Fig. 3b.

The results for both 2% and 3.5% Er:CaF$_2$ Q-switches are summarized in Table I. The best results were obtained with the (2%)Er:CaF$_2$ switch, using the cavity in Fig. 3b. A typical output pulse obtained is shown in Fig. 4, for this configuration. The Q-switched pulse was recorded using a fast InGaAs photodiode, and the Q-switched output energy was measured using a Scientech calorimeter.

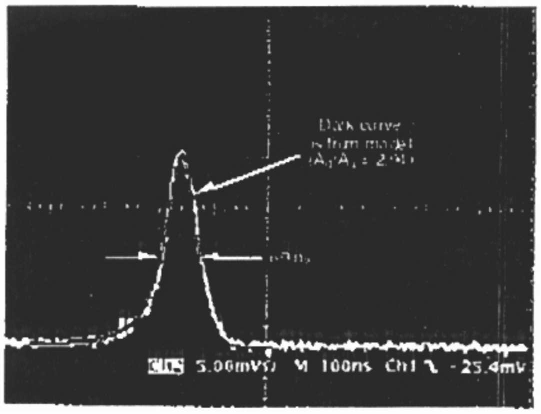

Figure 4. Q-switched pulse.

A saturable absorber Q-switch rate equation model was applied to the (2%)Er:CaF$_2$ Q-switch. Using the parameters from Table I (losses due to Fresnel reflections from the uncoated surfaces were also included), and the measured value for the absorption cross-section (σ_{eff}), the theoretical model predicted a pulsewidth of 18 ns and an output energy of 36.6 mJ. When the focusing parameter,[5] A_l/A_s, was adjusted to 2.94 in the model, the simulated output pulse shape was identical to experiment (see Fig. 4). The corresponding theoretical output energy was 19.3 mJ.

In conclusion, we have demonstrated a new saturable absorber Q-switch material, Er^{3+}:CaF$_2$, for the 1.54 µm Er:glass laser. We achieved reliable operation with output pulses of 11 mJ, 69 ns in a 17.5 cm laser cavity. The Er:CaF$_2$ did not exhibit any of the free-running problems previously encountered with Er:FAP, because of the rapid initial decay of its $^4I_{13/2}$ level. The theoretical modeling for the Q-switched pulse shapes was in good agreement with experimental data.

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Table I. Summary of Er:CaF$_2$ Q-switched laser experiments.

Q-switch; Thickness (mm)	Resonator cavity; Er:glass rod; Intracavity lens f.l.	Internal transmit. at 1533 nm	A_l/A_s (calc.)	Output mirror reflect. (%)	Output Energy (mJ)	Thresh. (J)	Free-run. output energy (mJ)	Q-sw. pulsewidth (ns)
(2.0%)Er:CaF$_2$; 1.0	Fig. 3b; 3 x 50 mm QE-7S; +5cm	0.80	12.9	94	11	46	162	69
(3.5%)Er:CaF$_2$; 1.1	Fig. 3a; 3 x 50 mm QE-7S; +7.6cm	0.72	6.2	88	3.3	205	not measured	129