U^{4+}:SrF_2 efficient saturable absorber *Q* switch for the 1.54 μm erbium:glass laser

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Saturable absorber *Q* switching of the Er:glass laser at 1533 nm using U^{4+}:SrF_2 has been obtained. *Q*-switched pulses of 3 mJ and 60 ns full width at half-maximum were achieved using a 2.69-mm-thick *Q* switch in a 14-cm-long plane-parallel cavity, with a 3×50 mm Kigre QE-7S Er:glass rod. The high absorption cross section of U^{4+}:SrF_2 resulted in efficient *Q*-switched operation (without intracavity focusing) in agreement with the theoretical predictions.

We have demonstrated saturable absorber *Q* switching of an Er:glass laser at 1533 nm using tetravalent uranium ions in strontium fluoride (U^{4+}:SrF_2). The *Q* switching was accomplished in a plane-parallel resonator cavity without intracavity focusing. U^{4+}:SrF_2 possesses a broad absorption feature,[1,2] which peaks close to the Er:glass wavelength (see Fig. 1).

Er:glass has been *Q* switched electro-optically, with a rotating mirror, and using frustrated total internal reflection.[3,4] These methods are usually efficient, but require additional power supplies and moving parts which increase the size, complexity, and cost of the laser system. Saturable absorber *Q* switching is the simplest and most compact method, but attempts to date have not been particularly fruitful. Er:glass saturable absorber *Q* switching using color centers[5] or the erbium ion in various hosts[6–8] has generally performed poorly or has required a certain amount of focusing of the light in the *Q*-switch material.

The *Q*-switching results were obtained using a Kigre 3×50 mm QE-7S Er:glass rod. The rod was pumped with a flash lamp pulse of about 600 μs full width at half-maximum (FWHM). The resonator cavity consisted of two flat mirrors separated by 14 cm (see Fig. 2 for experimental setup). Three different output mirror reflectivities were used in the experiments: 82%, 88%, and 94%. The other cavity mirror was 100% reflective at 1533 nm. The threshold for the free-running laser (i.e., with *Q* switch removed) was 13 J with the 94% output mirror, and about 15 J with the 82% mirror.

The U^{4+}:SrF_2 *Q* switches used were all cut from the same 2.3-cm-long rod. The crystal was originally thought to be U^{3+}:SrF_2, however, its absorption spectrum revealed features[1,2] clearly identified as U^{3+} and U^{4+}. Crystals of U^{3+}:CaF_2, in our possession, did not exhibit features attributable to U^{4+}. For our experiments, the "accidental" presence of U^{4+} was crucial for our results.

The *Q*-switch thicknesses were 1.37, 2.69, and 9.12 mm, with internal transmittances of 95%, 90%, and 71%, respectively. The *Q* switches were polished flat with parallel surfaces and were used uncoated in the experiments. The *Q*-switch surfaces were aligned parallel to the resonator cavity mirrors in all but one case where the 1.37 mm *Q* switch was placed at Brewster's angle. The absorption coefficient of the U^{4+}:SrF_2 was measured to be 0.38 cm^{-1} at the *Q*-switched wavelength of 1533 nm.

The results are summarized in Table I. A typical *Q*-switched pulse is shown in Fig. 3(a) (3 mJ, 60 ns) for the 2.69 mm *Q* switch and the 94% *R* output mirror. *Q*-switch pulses were recorded using an InGaAs diode detector and a Hewlett–Packard 54510A digital oscilloscope. The flashlamp pulse shown in Fig. 3(b) was recorded using a germanium diode. The timing of the *Q*-switch pulse is also shown in Fig. 3(b). Energy measurements were made using a Scientech 365 Calorimeter. The wavelength of the *Q*-switched output was 1533 nm, measured using a $\frac{1}{4}$ meter Jarrell-Ash monochromator. This was about 1 nm shorter than the peak of the free-running laser. The output beam diameter of the *Q*-switched laser operated just above threshold was only about $\frac{1}{2}$ that of the free-running laser, and the beam divergence of the *Q*-switched laser was smaller, indicating that suppression of higher order transverse modes was occurring with the *Q*-switched laser.

The shortest *Q*-switched pulse obtained in our experiments was 20 ns FWHM using the 9.12 mm *Q* switch and the 88% *R* output mirror (see Table I). However, this configuration produced damage in the *Q* switch and the lasing ceased after only a few pulses. Afterwards, damage could

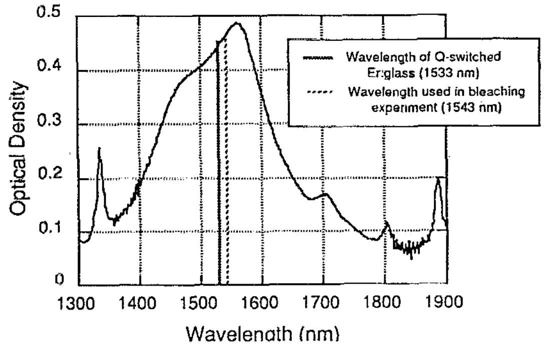

FIG. 1. Absorption spectrum of U^{4+}:SrF_2 near 1.54 μm.

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[a] Also with Hughes Aircraft Company at El Segundo, CA 90245.

[b] Also with TRW Space and Defense Group at Redondo Beach, CA 90278.

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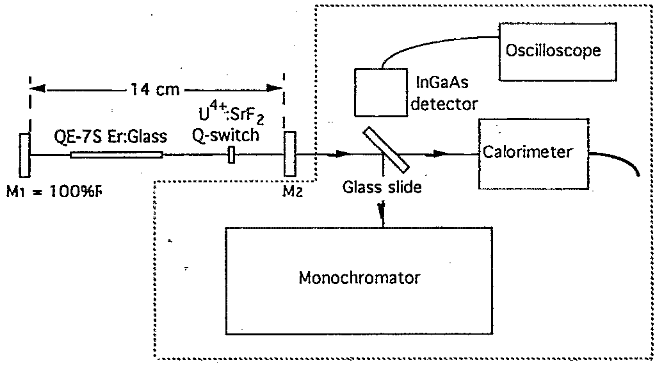

FIG. 2. Experimental setup.

clearly be seen inside the crystal all along the beam path. In addition, threshold was extremely high for this Q switch, due to the lower transmittance of this Q switch and the stored energy limit of the 5-cm-long Er:glass rod.

The saturation fluence of the U^{4+}:SrF$_2$ was measured using a Raman-shifted Nd:YAG laser at 1543 nm. The 1543 nm light was focused to a 1.3 mm spot diameter (e^{-2} point) with a FWHM pulse width of 15 ns and a FWHM spectral linewidth of less than one nanometer. The results of this experiment and the 9.12 mm Q switch are shown in Fig. 4.

Assuming that the lifetime of the upper level of U^{4+}:SrF$_2$ is long compared to the bleaching pulse, the Frantz–Nodvik equation,[9] modified for absorption, can be used to model the experimental results. Then, the transmittance T is given by

$$T=\frac{F_{\mathrm{sat}}}{F_{\mathrm{in}}}\ln\left\{T_0\left[\exp\left(\frac{F_{\mathrm{in}}}{F_{\mathrm{sat}}}\right)-1\right]+1\right\}, \tag{1}$$

where F_{in} is the incident fluence (J/cm^2), F_{sat} is the saturation fluence, and T_0 is the small-signal transmittance. A least-squares fit to the experimental data yielded a saturation fluence of 1.86 J/cm^2 (see Fig. 4). Using $F_{\mathrm{sat}}=h\nu/\sigma$, where σ is the absorption cross section, we obtain a cross section of 6.9×10^{-20} cm^2 at 1543 nm. The cross section at the Er:glass Q-switched lasing wavelength of 1533 nm should not be significantly different (see Fig. 1).

The rate equations for the case of a saturable absorber Q switch with a three-level laser are given[10,11] by

$$\frac{d\phi}{dt}=(K_gN_g-K_aN_a-\gamma_c)\phi, \tag{2}$$

TABLE I. Summary of U^{4+}:SrF$_2$ Q-switch experimental results.

Output mirror reflectivity	Q-switch thickness (mm)	Q-switched output energy (mJ)	Q-switched full pulse width (ns)	Threshold (J)
94%	1.37	2	220	15
94%	1.37 (Brewster)	3	91	17
94%	2.69	3	60	20
88%	9.12	10–20	20	115–156
82%	1.37	1.2	590	18
82%	2.69	5	130	23

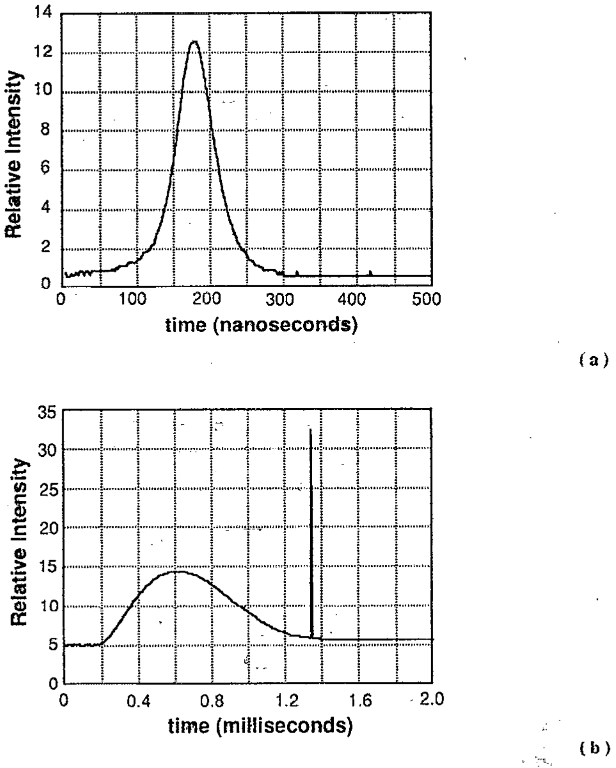

FIG. 3. (a) Q-switch pulse; (b) flashlamp pulse with Q-switch pulse appearing as spike at trailing end of lamp waveform.

$$\frac{dN_g}{dt}=-\gamma K_gN_g\phi, \tag{3}$$

$$\frac{dN_a}{dt}=-K_aN_a\phi, \tag{4}$$

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, g_1 are the upper and lower laser level degeneracies, respectively. It was assumed

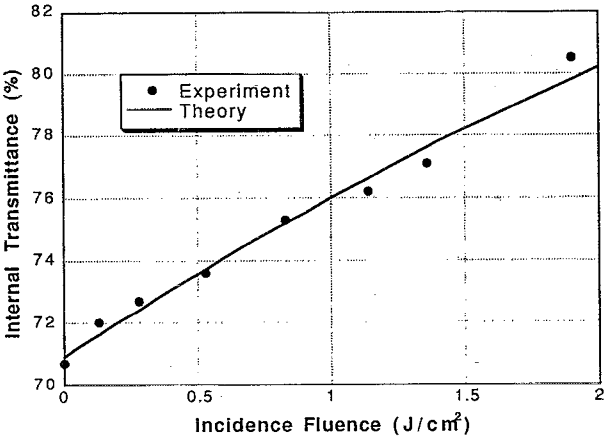

FIG. 4. 1543 nm bleaching of U^{4+}:SrF$_2$. Saturation fluence=1.86 J/cm^2.

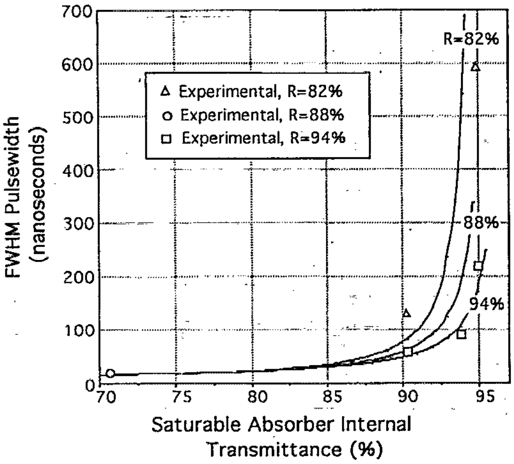

FIG. 5. Theoretical Q-switched pulsewidth vs experiment. Solid lines represent theory.

$g_1=g_2$, or $\gamma=2$, here. The coupling coefficients K_i are given by $K_i=\sigma_i/t_1A_i$, where $\sigma_{g,a}$ are the gain and absorber cross sections, $A_{g,a}$ are the areas of the photon beam in the gain and absorber media, and t_1 is the one-way photon cavity transit time. The upper-state decay lifetime was assumed infinitely long, compared with the Q-switched pulse, for both Er:glass and U^{4+}:SrF_2.

We numerically solved Eqs. (2)–(4) using cross sections of 0.8×10^{-20} and 6.9×10^{-20} cm^2, respectively, for the Er:glass and U^{4+}:SrF_2. The theoretically predicted pulsewidths are plotted together with the experimental data as a function of saturable absorber transmittance in Fig. 5. A single-pass nonsaturable loss of 5% was assumed in the model. Agreement between theory and experiment was good.

In conclusion, we have demonstrated a new efficient passive Q switch for the Er:glass laser which can operate in a simple plane-parallel cavity without the need for intracavity focusing. The absorption cross section of the U^{4+}:SrF_2 saturable absorber is several times higher than the stimulated emission cross section of the Er:glass and therefore produces efficient Q switching without intracavity focussing. Future research in this area will include investigation of the U^{4+} ion in other crystalline hosts.

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