Divalent Uranium and Cobalt Saturable Absorber Q-switches at 1.5 μm

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We report on passive Q-switching of the Er:glass laser using both slowly-relaxing (U^{2+} in BaF_2, CaF_2, and SrF_2) and fast-relaxing (Co^{2+} in $Y_3Sc_2Ga_3O_{12}$(YSGG) and $Y_3Al_5O_{12}$ (YAG)) saturable absorbers.[1,2]

Divalent uranium ions possess a broad absorption band,[3-5] in the di-fluoride crystals, which peaks close to the Er:glass emission wavelength (see Figure 1). Divalent cobalt ions in garnet crystals also have a broad band absorption[6] near 1.5 μm (see Figure 2).

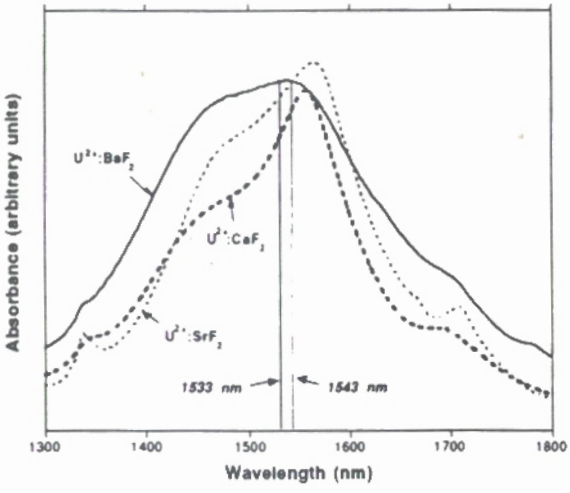

Figure 1. Room temperature absorption spectra of U^{2+}:CaF_2, U^{2+}:SrF_2, and U^{2+}:BaF_2 near 1.5 μm.

The U^{2+} absorption cross-sections were determined by bleaching the crystals using a Raman-shifted Nd:YAG laser at 1543 nm. The Full-Width at Half-Maximum (FWHM) pulsewidth of the bleaching radiation was 14 nanoseconds, and the FWHM spectral linewidth was less than one nanometer. The excited-state lifetimes of U^{2+} in CaF_2, SrF_2, and BaF_2 (see Table I) are long compared to the 1543 nm pulse duration, therefore the Frantz-Nodvik equation,[7] modified for absorption, was used to analyze the bleaching results. The measured cross sections are summarized in Table I.

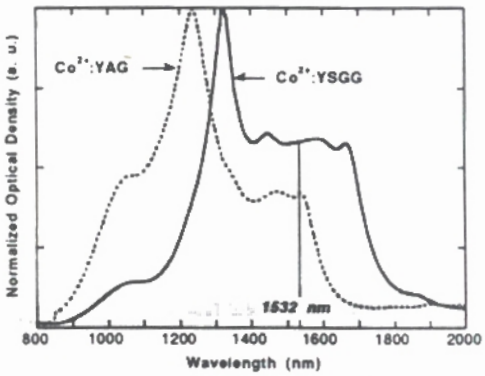

Figure 2. Co^{2+}:YSGG and Co^{2+}:YAG absorption spectra.

Table I. Spectroscopic parameters of Q-switch materials.

Material	α_0 at 1533nm (cm^{-1})	300 K lifetime (μsec)	Cross-section (x 10^{-20}, cm^2)
U:BaF_2	0.58	40	5
U:CaF_2	1.26	5	7
U:SrF_2	1.05	25	7

The relaxation lifetime of the Co^{2+}-doped crystals was determined to be fast compared to the 1543 nm bleaching pulse duration, using a pump-probe method. The saturation intensities at 1543 nm for both Co:YSGG and Co:YAG are given in Table II. Transmittance as a function of incident intensity for Co:YSGG is shown in Figure 3. The Co^{2+}:YSGG crystal used in this work was grown using the standard Czochralski method. The crystal boule was 1.3" x 6", grown along the <111> direction, using an undoped YSGG seed. The cobalt concentration was 2% at. wt., and silicon was added to the melt for charge compensation. The Co:YAG crystal was grown in a similar fashion.

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Table II. Saturation intensities of Co^{2+}-doped crystals.

Crystal	Sample thickness (mm)	Small-signal internal transmittance @ 1543 nm	1543 nm α_o (cm^{-1})	1543 nm saturation intensity ($x10^6$ MW/cm^2)
Co:YSGG	8.92	0.054	3.27	180
Co:YAG	3.91	0.80	0.57	140

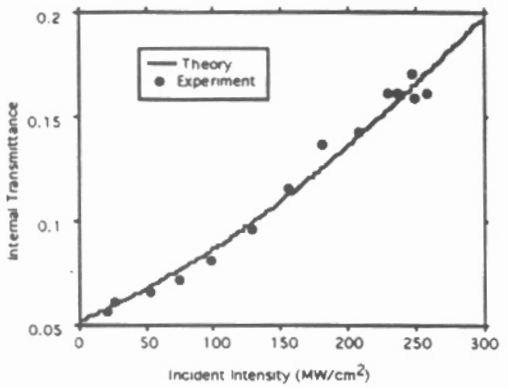

Figure 3. Absorption saturation of Co:YSGG at 1543 nm.

Fluorescence lifetime measurements for the U^{2+}-doped crystals were carried out by pumping the crystals with the Raman-shifted Nd:YAG laser. The fluorescence (~2.6 μm)[3] was measured using an InAs detector with a germanium crystal filter to block the pump light. The observed fluorescence started immediately following the excitation pulse and was a single exponential to at least three e^{-1} lifetimes. Lifetime measurements have been made from about 300 K to 400 K and are plotted in Figures 4 and 5. The room temperature values are summarized in Table I.

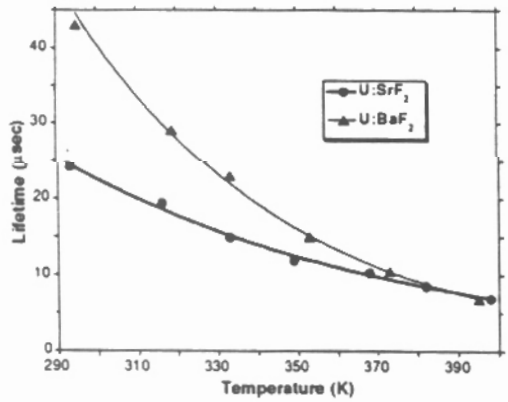

Figure 4. U^{2+}:SrF_2 and U^{2+}:BaF_2 fluorescence lifetime as a function of temperature.

The U:SrF_2, U:CaF_2 and U:BaF_2 crystals (provided by Dr. Robert Sparrow, Optovac) were evaluated as Q-switches in an Er:glass laser resonator. A Kigre 3 x 50 mm (QE-7S) Er:glass rod was used for the SrF_2 and BaF_2 Q-switches. The rod was flashlamp-pumped in a Kigre pump head. The U:CaF_2 Q-switch was used in conjunction with a 4 x 76 mm (QE-7S) Kigre rod in an unoptimized pump head designed for a much larger rod. The resonator cavities consisted of two flat mirrors with physical lengths of 10 cm for the U:SrF_2 and U:BaF_2, and 15.5 cm for U:CaF_2. The resonator output mirror reflectivity was 80% for the SrF_2 Q-switch, and 94% for CaF_2 and BaF_2. The Q-switching results are summarized in Table III. A typical pulse observed for the U:CaF_2 Q-switch is shown in Figure 5. No damage to the U:CaF_2 crystal was observed even after several shots.

The Q-switched pulse (4mJ, 20ns), shown in Fig. 6, was obtained for the Co:YSGG crystal with the same Er:glass pump head used for the U:CaF_2 Q-switch. However, a 94%R concave (+2.5 cm curvature) outcoupler and an intracavity +5cm lens were used to provide focussing into the Q-switch crystal. The cavity length was 22.5 cc. Q-switching did not occur with either of the Co^{2+}-doped crystals in an (unfocussed) plane-parallel cavity. 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 20 ns Q-switched pulse was obtained without damage to the Co:YSGG crystal.

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

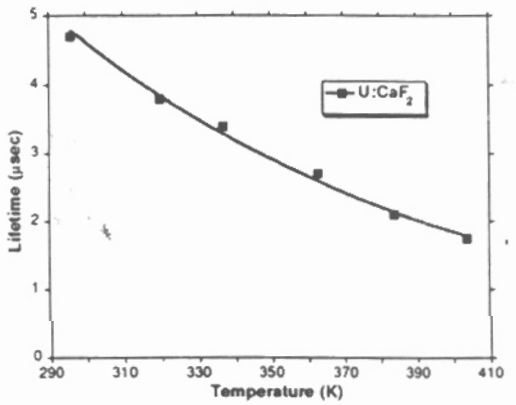

Figure 5. U^{2+} fluorescence lifetime as a function of temperature for U^{2+}:CaF_2.

Table III. Uranium Q-switch results.

Q-Switch Matl.	Thickness (mm)	Internal Transmit. (%)	Output energy (mJ)	Measured pulsewidth (ns)	Threshold (J)
U:BaF_2	1	94	1	280	10.5
U:SrF_2	1 (Brewster)	87	11	45	15
U:CaF_2	4	60	3	21	86

Table IV. Cobalt Q-switch results.

Q-Switch Matl.	Q-switch thickness (mm)	Int. Trans. (%)	FWHM (ns)	Output energy (mJ)	Threshold (J)
Co: YSGG	0.5	85	20	4	40
Co: YAG	8.1	58	88	≈1	107

We modeled the Q-switch operation using saturable absorber Q-switch rate equations.[8,9] The uranium-doped crystals were modeled in the slowly-relaxing regime and the cobalt-doped crystals as fast-relaxing absorbers. The agreement between theory and experiment was very good, especially for the (optically-thin) U:SrF_2 and U:BaF_2 Q-switches.

In conclusion, we have demonstrated that U^{2+}:SrF_2 and U^{2+}:BaF_2 are efficient Q-switches for the Er:glass laser at 1533 nm. We have also demonstrated that 20 nanosecond pulses can be obtained with U^{2+}:CaF_2 and Co^{2+}:YSGG Q-switches, without damage. More efficient operation with the latter Q-switches are anticipated in an optimized Er:glass laser system.

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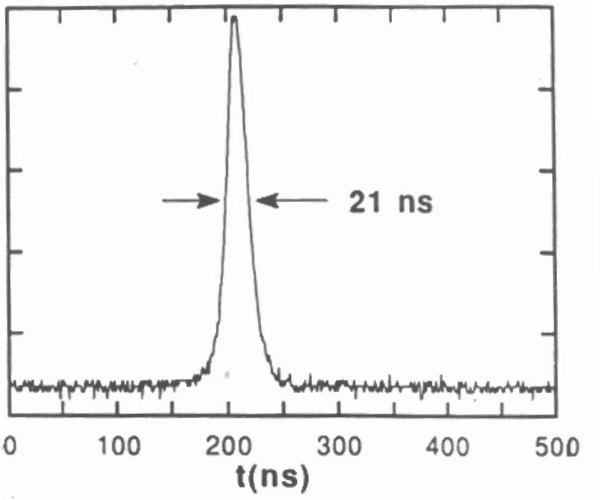

Figure 5. Experimental pulse for U:CaF_2 Q-switch.

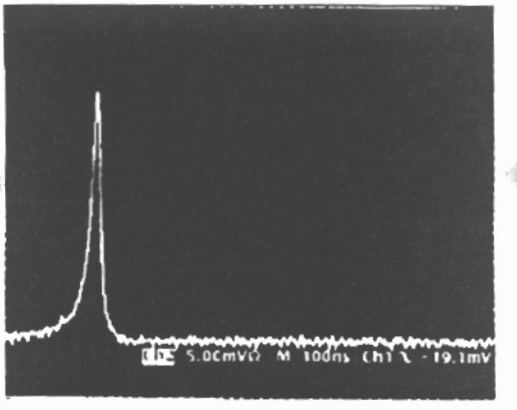

Figure 6. Experimental pulse for Co:YSGG Q-switch. (20 ns, full-width at half maximum).

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