

# Passive Q-switch at 1.53 $\mu\text{m}$ using divalent uranium ions in calcium fluoride

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Using a  $\text{U}^{2+}:\text{CaF}_2$  passive Q-switch for the Er:glass laser, 20 ns, 3 mJ pulses were obtained. This is the shortest duration passive Q-switched pulse obtained for this laser without intracavity focusing and without optical damage. The measured  $\text{U}^{2+}:\text{CaF}_2$  absorption cross section and relaxation lifetime are compared with those of  $\text{U}^{2+}:\text{SrF}_2$  and  $\text{U}^{2+}:\text{BaF}_2$ . © 1995 American Institute of Physics.

## I. INTRODUCTION

$\text{U}^{2+}$  in  $\text{SrF}_2$  has been used previously as a 1.53  $\mu\text{m}$  Q-switch for the Er:glass laser.<sup>1</sup> With this saturable absorber, Q-switched pulses as short as 20 ns were achieved, but damage was always a problem for pulsewidths less than about 40 ns, full width at half maximum (FWHM). Now, 20 ns Q-switched pulses without damage have been obtained using  $\text{U}^{2+}:\text{CaF}_2$ . This new Q-switch material operates in a plane-parallel resonator cavity without intracavity focusing.

The identification of the uranium ion valence responsible for the broad absorption band near 1.5  $\mu\text{m}$  in di-fluoride crystals has been controversial. Several early papers<sup>2,3</sup> associated this absorption feature with  $\text{U}^{4+}$ . However, later papers by Hargreaves<sup>4,5</sup> attributed this absorption to  $\text{U}^{2+}$ . Figure 1 shows a comparison between the measured 300 K absorption spectra for the crystals used here with the  $\text{U}^{2+}$  spectrum from Ref. 5. Although the latter is at low temperature, several peaks can be seen to match the room temperature spectra. The Hargreaves' valence identification is used in this paper.

## II. EXPERIMENTAL RESULTS AND MODEL

### A. Spectroscopic measurements

$\text{U}^{2+}$  in  $\text{CaF}_2$  exhibits a broad absorption band which peaks near 1.58  $\mu\text{m}$ , similar to the one for  $\text{U}^{2+}$  in  $\text{SrF}_2$  and  $\text{BaF}_2$  (Fig. 2). The energy level diagram<sup>4</sup> for  $\text{U}^{2+}:\text{CaF}_2$  is shown in Fig. 3. When pumped near 1.5  $\mu\text{m}$ , the  $\text{U}^{2+}$  ion is promoted from the ground state ( $^5I_4$ ) to a higher excited state, which then quickly decays to the metastable state ( $^3I_5$ ). Fluorescence, as a result of transitions from the metastable state back to the ground state, peaks at about 2.6  $\mu\text{m}$ .<sup>6</sup> The luminescence peaks measured with 1.53  $\mu\text{m}$  pumping of  $\text{U}^{2+}$  in the  $\text{BaF}_2$  and  $\text{SrF}_2$  crystals were 2.5 and 2.6  $\mu\text{m}$  at room temperature. The weakness of the  $\text{U}:\text{CaF}_2$  fluorescence prevented an accurate wavelength measurement in our setup; however, it should have a similar value to those observed with the uranium-doped  $\text{SrF}_2$  and  $\text{BaF}_2$  crystals.

The saturation fluence ( $F_{\text{sat}}$ ) was measured at 1.543  $\mu\text{m}$  using a Raman-shifted Nd:YAG laser.<sup>1</sup> The effective absorption cross section was obtained from  $\sigma_{\text{eff}} = h\nu/F_{\text{sat}}$ . The  $\sigma_{\text{eff}}$  measured for  $\text{U}^{2+}:\text{CaF}_2$  (see Table I) is nearly the same (within experimental error) as previously measured<sup>1</sup> for  $\text{U}^{2+}:\text{SrF}_2$ .  $\text{U}^{2+}:\text{BaF}_2$  has a measured cross section of about two-thirds that of  $\text{CaF}_2$  and  $\text{SrF}_2$ . The cross section values have been corrected for the Gaussian transverse profile of the 1.543  $\mu\text{m}$  bleaching laser beam. The  $\text{U}^{2+}$  concentrations  $n$  were estimated to be of the order of  $10^{19} \text{ cm}^{-3}$  for all three crystal hosts, using

$$n = \frac{-\ln T_0}{L\sigma_{\text{eff}}}, \quad (1)$$

where  $T_0$  is the small-signal internal transmittance and  $L$  is the thickness of the crystal.

The lifetime of the metastable state was measured by pumping at 1.543  $\mu\text{m}$  and observing the decay of the  $\sim 2.6 \mu\text{m}$  fluorescence using an InAs detector. The excitation light was blocked from the detector using a germanium crystal. The observed fluorescence reached a maximum within 50 ns (faster than the response time of the detector) after the 1.54  $\mu\text{m}$  excitation pulse and decayed as a single exponential component to at least three  $e^{-1}$  lifetimes. The lifetime was

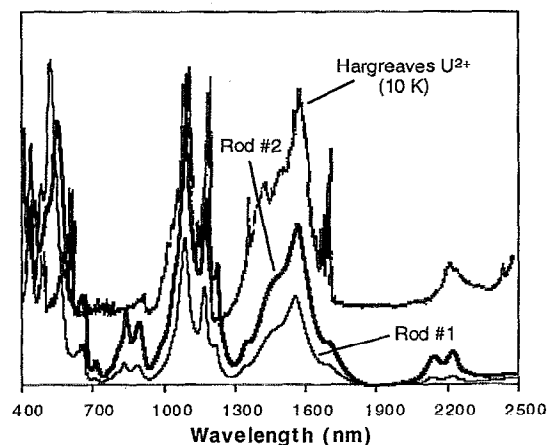


FIG. 1. Comparison of published low-temperature  $\text{U}^{2+}:\text{CaF}_2$  absorption spectrum from Ref. 5, and measured room temperature spectra of  $\text{U}:\text{CaF}_2$  crystal rods.

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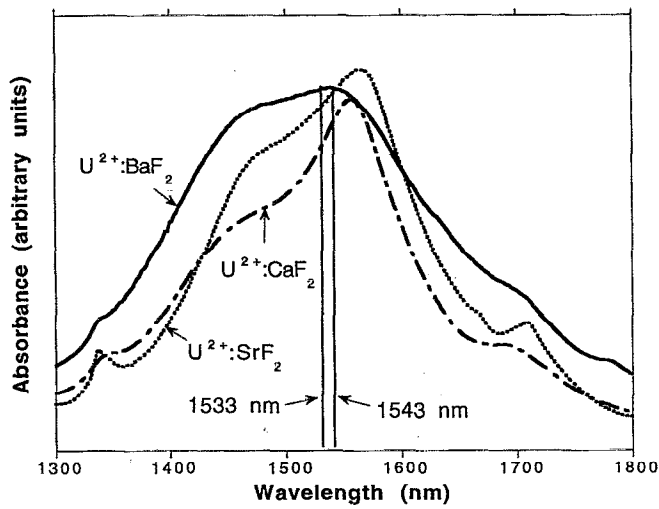


FIG. 2. Room temperature absorption spectra of  $U^{2+}:\text{CaF}_2$ ,  $U^{2+}:\text{SrF}_2$ , and  $U^{2+}:\text{BaF}_2$  near  $1.5 \mu\text{m}$ .

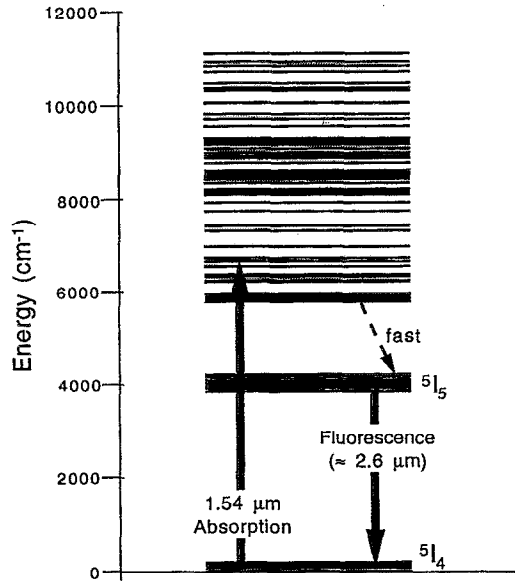


FIG. 3.  $U^{2+}:\text{CaF}_2$  energy level diagram (after Hargreaves).

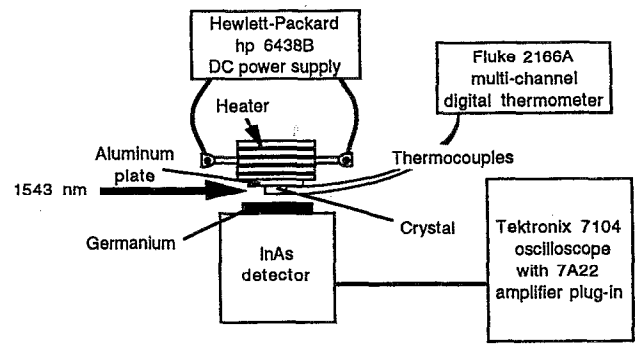
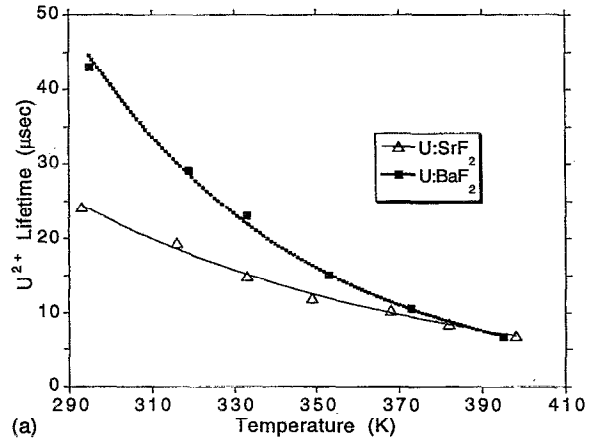
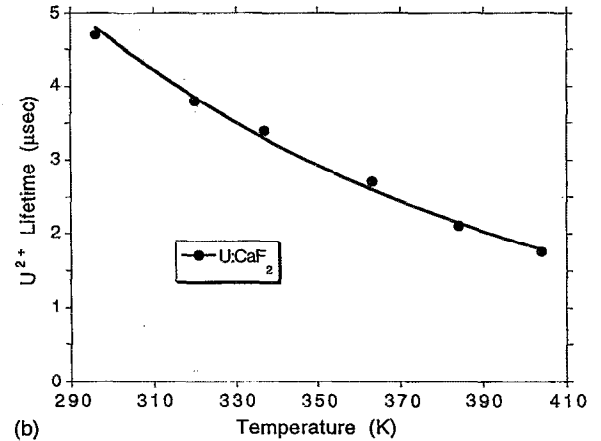


FIG. 4. High-temperature fluorescence lifetime experimental apparatus.



(a)



(b)

FIG. 5.  $U^{2+} (^5I_5)$  fluorescence lifetime as a function of temperature for (a)  $U:\text{SrF}_2$  and  $U:\text{BaF}_2$  and (b)  $U:\text{CaF}_2$ .

TABLE I. Measured  $1.543 \mu\text{m}$  absorption cross sections of  $U^{2+}$ :difluoride crystals.

Crystal	Sample thickness (mm)	Small-signal transmittance at $1.543 \mu\text{m}$	1.543		Calculated $U^{2+}$ concentrations ( $\times 10^{19} \text{cm}^{-3}$ )
			$\mu$	$\alpha_0$ ( $\text{cm}^{-1}$ )	
$U:\text{SrF}_2$ , rod No. 1	9.12	0.72	0.36	$7.6 \pm 1.7$	0.47
$U:\text{SrF}_2$ , rod No. 2	2.5	0.84	0.70	$7.3 \pm 1.1$	0.96
$U:\text{CaF}_2$ , rod No. 1	7.15	0.68	0.54	$7.0 \pm 1.1$	0.77
$U:\text{CaF}_2$ , rod No. 2	4.05	0.60	1.26	$7.1 \pm 1.1$	1.8
$U:\text{BaF}_2$	4.5	0.68	0.86	$4.9 \pm 1.7$	1.8

TABLE II.  $Q$ -switch results for  $U^{2+}:\text{CaF}_2$ .

U:CaF <sub>2</sub> $Q$ -switch	Laser resonator length (cm)	$Q$ -switch thickness (mm)	Pulsewidth (ns)		Output energy (mJ)	Threshold (J)
			Expt.	Theory		
Rod No. 1	26.5	7.15	40	26	2.5	86
Rod No. 2	26.5	4.05	45	24	3.3	86
Rod No. 2	15.5	4.05	21	15	2.8	86

also measured at elevated temperatures using the setup shown in Fig. 4. The crystal was mounted on an aluminum plate with metallic tape. The aluminum plate was attached to a heater whose temperature was controlled with a dc power supply. The temperature of the crystal was monitored with a thermocouple. Lifetime measurements as a function of crystal temperature are shown in Fig. 5.

### B. $Q$ -switching results and rate equation model

In Table II we summarize the results obtained using the  $U^{2+}:\text{CaF}_2$   $Q$ -switches. The Er:glass rod (Kigre QE-7S,  $4 \times 76$  mm) was flashlamp pumped. The resonator was plane-parallel (flat mirrors) with a 94% reflective outcoupler. A high threshold was observed because the pump cavity was designed for a larger rod and was not optimized. The results for both  $Q$ -switches listed in Table II were obtained without optical damage. The resonator length was reduced with

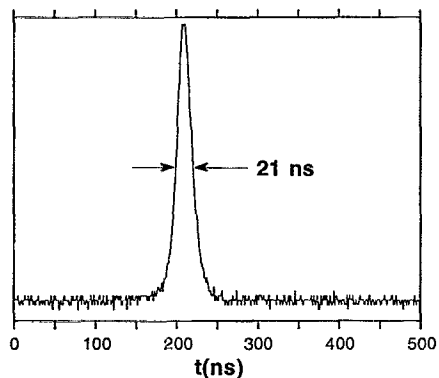


FIG. 6. Er:glass output pulse obtained with a  $U^{2+}:\text{CaF}_2$   $Q$ -switch.

$Q$ -switch No. 2 in order to shorten the pulsewidth. A typical pulse obtained with the second  $Q$ -switch (4.05 mm thick), in the shorter cavity, is shown in Fig. 6.

The standard saturable absorber  $Q$ -switch rate equations<sup>7,8</sup> predict shorter pulsewidths than observed experimentally (see Table II). In our prior work with  $U:\text{SrF}_2$ ,<sup>1</sup> the agreement with this theory was good. However, in that case the insertion losses of the  $Q$ -switches used were low (typically  $\leq 10\%$ ). The rate equation theory assumes a uniform distribution of losses throughout the resonator cavity. In the case of high  $Q$ -switch insertion losses ( $\geq 30\%$  with the  $U:\text{CaF}_2$   $Q$ -switches) this assumption may not hold. This point is currently under study.

### III. SUMMARY

Using a  $U^{2+}:\text{CaF}_2$  saturable absorber  $Q$ -switch crystal, 20 ns pulses were obtained without crystal damage and without focusing elements. Antireflective (AR) coating of the  $Q$ -switches and optimization of the pump cavity should result in a significantly improved overall performance.

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