

# Er<sup>3+</sup>:Sr<sub>5</sub>(VO<sub>4</sub>)<sub>3</sub>F: A Potential Passive Q-Switch for Er-Glass Lasers

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## Abstract

Er<sup>3+</sup> in multi-site Sr<sub>5</sub>(VO<sub>4</sub>)<sub>3</sub>F is evaluated spectroscopically for its potential as an intracavity saturable absorber passive Q-switch for Er-glass lasers.

## Introduction

The fluoro-apatite crystal Ca<sub>5</sub>(PO<sub>4</sub>)<sub>3</sub>F (FAP) doped with Er<sup>3+</sup> has been reported by Spariosu et al.[1] to perform reasonably well as an intracavity saturable absorber passive Q-switch for the Er-glass laser at 1.53 μm, an eye-safe wavelength. Free-running output following the giant pulse and a necessity for intracavity focussing indicate that Er:FAP is still not ideal. Hence, there is reason to investigate Er in other hosts. This paper presents a spectroscopic analysis of the Q-switch potential for the similar apatite crystal Er:Sr<sub>5</sub>(VO<sub>4</sub>)<sub>3</sub>F (Er:SVAP).

## Experiment

The Er:SVAP crystals studied here were produced in the CREOL crystal growth facility using the conventional Czochralski technique. SVAP is hexagonal with space group P6<sub>3</sub>/m and lattice parameters  $a = 10.0077 \text{ \AA}$  and  $c = 7.4342 \text{ \AA}$  [2].

The room temperature absorption measurements presented here were performed using a Fourier spectrometer with quartz-halogen source, quartz beam-splitter and a liquid-nitrogen-cooled InSb detector.

Site selective photoluminescence was achieved using

a cw Ar-laser pumped dye laser (LDS dye). The laser's single-mode frequency and linewidth ( $< 1 \text{ cm}^{-1}$ ) are determined spectroscopically using the high resolution Fourier spectrometer. The photoluminescence is also collected by the Fourier spectrometer with a quartz beamsplitter and a nitrogen-cooled InGaAs detector. The sample was cooled to 2 K in a variable temperature optical-access liquid-helium cryostat. The measurements at 80 K were performed using a liquid nitrogen cold-finger cryostat.

For luminescence-decay measurements, Er<sup>3+</sup> ions were excited to their <sup>4</sup>I<sub>9/2</sub> level using 0.5 second pulses of a ~10 mW 796 nm laser diode having a turn-off time less than 100 μs. The signal was collected by the InGaAs detector, which was shielded from the laser light by a 950 nm long-pass interference filter, and 100 decays were averaged. Emission from the <sup>4</sup>I<sub>13/2</sub> level was the only significant contribution to the measured signal, as determined from photoluminescence spectroscopy using the same detector.

## Results and Discussion

In order to be useful as a passive Q-switch, the absorption profile of Er:SVAP needs to match the Er-glass emission profile. Fig. 1 presents the <sup>4</sup>I<sub>15/2</sub> → <sup>4</sup>I<sub>13/2</sub> transmission spectrum of 1.24 cm thick 1% Er:SVAP at 300 K. The Er-glass emission spectrum[1] peaks near 1.53 μm, and this wavelength is indicated in Fig. 1. The absorption of Er:SVAP appears adequately matched.

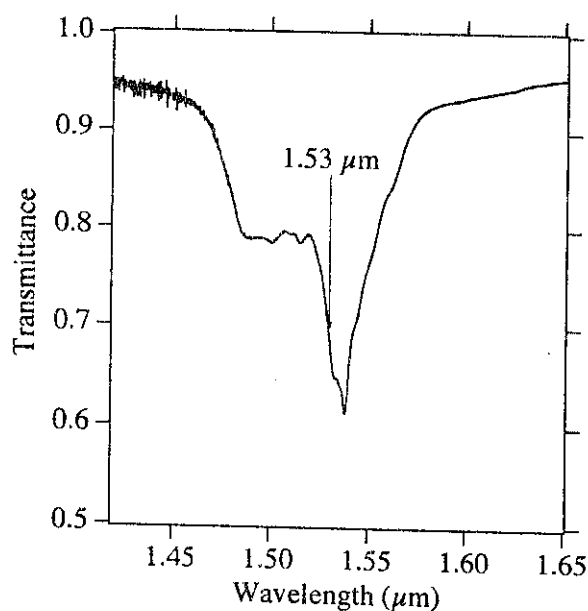


Figure 1. Er:SVAP  $4I_{15/2} \rightarrow 4I_{13/2}$  300K transmission spectrum. The sample thickness is 1.24 cm. The nominal Er concentration is 1 %.

For efficient passive Q-switching, the absorption cross section of the intracavity saturable absorber  $\sigma_a$  should be larger than the gain-medium cross section  $\sigma_g$  [3]. We assume 1% actual Er concentration, use an SVAP unit cell volume[2] of  $644.8 \text{ \AA}^{-3}$  with ten  $\text{Sr}^{2+}$  sites per cell[4], and use the absorption coefficient at  $1.53 \mu\text{m}$  of  $0.26 \text{ cm}^{-1}$  to obtain  $\sigma_a = 1.7 \times 10^{-21} \text{ cm}^2$ . Applying the same assumptions and method, with the absorption spectrum from [1], and a unit cell volume[2] of  $524.43 \text{ \AA}^3$  gives  $\sigma_a = 3.3 \times 10^{-21} \text{ cm}^2$  for Er:FAP. Hence,  $\sigma_a$  is about two times smaller for Er:SVAP than for Er:FAP, and this favors FAP over SVAP as a passive Q-switch.

Our estimate of the Er:FAP  $\sigma_a$  is 4.5 times smaller than the estimate in [1]. Our values for both FAP and SVAP are smaller than  $\sigma_g$  at the  $1.53 \mu\text{m}$  peak ( $7 \times 10^{-21} \text{ cm}^2$ ) reported for KIGRE QE-7 Er:glass[1]. An underestimate of  $\sigma_a$  can result from an overestimate of the Er concentration since  $\sigma = \alpha/N$ . In the case of Nd doping in SVAP, actual concentrations are 4 to 6 times smaller than nominal concentrations[5], and a similar situation is likely to occur for Er doping. Hence our  $\sigma_a$  values are lower bounds. A 5-fold increase in  $\sigma_a$  is

reasonable, would reconcile our values with [1], and would make  $\sigma_a > \sigma_g$  for both crystals.

To prevent free running operation after the Q-switch pulse, the lifetime of the  $4I_{13/2}$  state should be short. Fig. 2 presents luminescence decay data for 80 and 300 K sample temperatures. The temperature dependence is small and the curves are rather exponential over 3 decades. A 300 K lifetime of 6.3 ms is found for Er:SVAP, which is smaller than the 10.5 ms lifetime reported[1] for Er:FAP, though still long compared to a typical Q-switch pulse width. Nevertheless, an Er:Glass laser using an Er:SVAP Q-switch is likely to exhibit less free running operation after the giant pulse than was observed using the Er:FAP Q-switch[1].

Addition of  $\text{Nd}^{3+}$  can shorten the  $\text{Er}^{3+} 4I_{13/2}$  lifetime via energy transfer to the  $\text{Nd}^{3+} 4I_{15/2}$  level and subsequent non-radiative decay. Trace amounts of  $\text{Nd}^{3+}$  ( $\sim 0.005 \text{ at. \%}$ ) are detected spectroscopically in our Er:SVAP crystal. Though the spectral overlap for Er  $\rightarrow$  Nd transfer is strong in SVAP[6], the closely exponential curves in Fig. 2 suggest that the Nd concentration is too low to affect the Er luminescence decay.

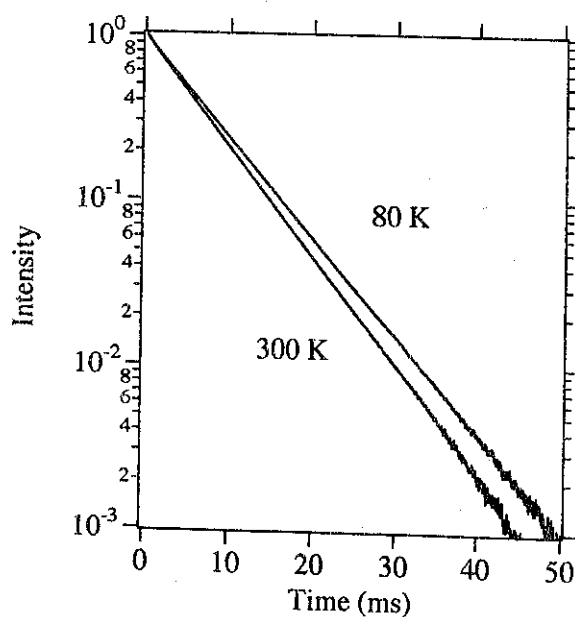


Figure 2. Er:SVAP  $4I_{13/2} \rightarrow 4I_{15/2}$  PL decay curves.

We present site-selective photoluminescence spectra at 2 K sample temperatures in Fig. 3. The  $\text{Er}^{3+} 4I_{9/2}$  band is selectively pumped with the dye laser, whose frequency is noted for each trace in Fig. 3. A variety of independent spectra are observed. Some of the lines are less than  $0.25 \text{ cm}^{-1}$  FWHM. Clearly, the number of possible crystal-field environments for Er in SVAP is large, as is expected from the necessity of charge compensation and from our earlier work on Nd in the same crystal[6]. Hence, the absorption spectrum in Fig. 1 contains contributions from many sites, with differing absorption cross sections and excited-state lifetimes likely.

Observation in Fig. 2 of nearly exponential decays does not automatically imply that all sites have the same lifetime. This is because energy transfer among sites favors emission from a single site at temperatures above 10 K, as was found for Nd in SVAP[6], and such

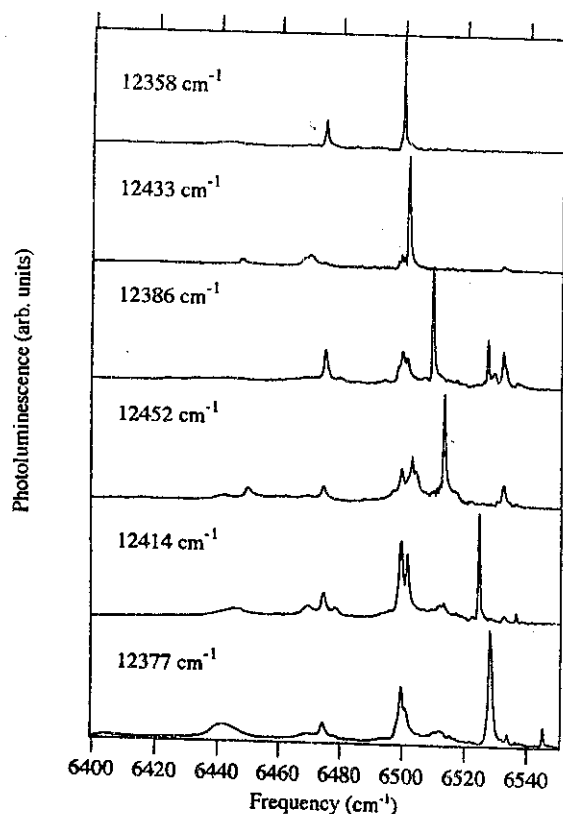


Figure 3. Er:SVAP site selective photoluminescence at 2K.

transfer might be too rapid to affect the luminescence decay curves on the time scales probed here at temperatures of 80 K and above. The measurements presented in Fig. 2 are only valid for times longer than the  $\sim 100 \mu\text{s}$  turn-off time of the laser diode pump, and characteristic intersite transfer times at Er concentrations of 1% can easily be less than this.

Fig. 4 presents site selective data at 80 K, which reveals an almost complete absence of selectivity. This verifies that all sites are strongly coupled at these temperatures, and demonstrates that rapid transfer is likely. The lifetime measured from Fig. 2 could in principle be much longer than that of the sites actually responsible for the absorption at  $1.53 \mu\text{m}$ .

The multi-site nature of SVAP (and FAP) complicates a purely spectroscopic analysis of Q-switch potential and must be remembered when considering the results above and in [1]. A thorough characterization of the multiple site contributions and of the dynamic interactions among them is necessary for a complete understanding. A spectroscopic study of these dynamic effects will require a high-resolution time-resolved technique such as we have recently been funded

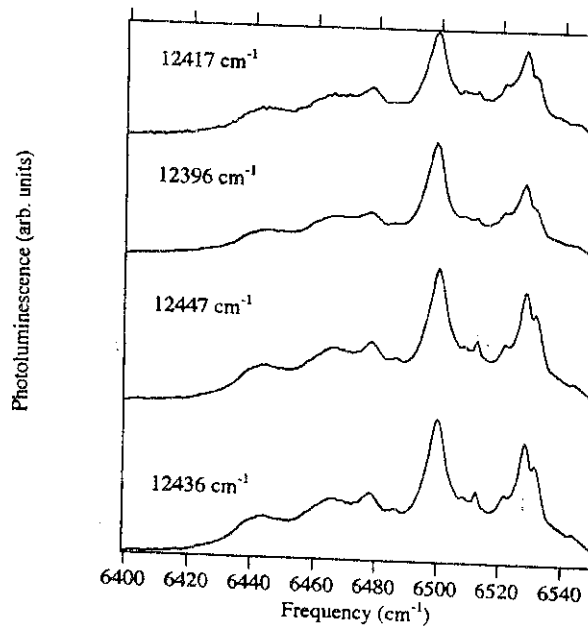


Figure 4. Er:SVAP site selective photoluminescence at 80 K. The laser frequency used to excite the sample is given for each trace.

to develop[7]. Ignoring such complications for now, as was done in [1], we conclude that Er:SVAP will be adequately efficient as a passive Q-switch for Er:glass lasers at 1.53  $\mu\text{m}$  and that free running operation after the Q-switch pulse will be less than for Er:FAP. However, further interest in either of the Er-doped apatites is likely to be overshadowed by the recent superior performance demonstrated for  $\text{U}^{4+}:\text{SrF}_2$  [8], whose absorption cross section is at least 8 times larger than that of Er:SVAP.

### Acknowledgments

This work is supported by AFOSR/DURIP grant #F49620-95-1-0075 and by the University of Central Florida Division of Sponsored Research. The authors thank Bruce Chai for providing the crystal.

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