NEW SATURABLE ABSORBER Q-SWITCH MATERIALS FOR SOLID STATE LASERS

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ABSTRACT

We have investigated new solid-state passive Q-switch materials for the Er:glass laser at 1.53 µm. Saturable absorber Q-switching has been obtained using Er^{3+}:$Ca_5(PO_4)_3F$, Er^{3+}:CaF_2, and U^{4+}:SrF_2.

INTRODUCTION

Er:glass lasers are interesting and useful for a large number of applications because they emit in a narrow eye-safe spectral region around 1.54 µm and coincide with the maximum transmission of silica fibers. Uses for eyesafe lasers include communications, optical atmospheric data, traffic enforcement, helicopter wire avoidance, and air defense.[1,2] Many of these applications require short pulses with high peak power such as can be obtained by Q-switching the Er:glass laser.

While saturable absorber Q-switching is simple and inexpensive, conventional methods of Q-switching the Er:glass laser have employed mechanical or electro-optical devices. Recently, our group reported on Er:glass saturable absorber Q-switching using Er:$Ca_5(PO_4)_3F$ (or Er:FAP).[3] We now report on two additional passive Q-switches for Er:glass (Er^{3+}:CaF_2 and U^{4+}:SrF_2), as well as new results with Er:FAP.

SATURABLE-ABSORBER Q-SWITCH THEORY

Saturable absorber Q-switching, for a 3-level laser, can be described using the following coupled differential equations:[4,5]

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$$\frac{dn}{dt} = [\, K_g N_g \ - K_a N_a - \gamma_c \,]\, n \qquad (1)$$

$$\frac{dN_g}{dt} = - \ \gamma K_g N_g \, n \qquad (2)$$

$$\frac{dN_a}{dt} = - \, K_a N_a \ n \qquad (3)$$

where n is the cavity photon number, $K_i = \sigma_i/t_1 A_i$ $(i = g,a)$, $\sigma_{g,a}$ are the stimulated emission and absorption cross-sections for the gain and saturable absorber media, respectivley, and t_1 is the single-pass photon transit time. $A_{g,a}$ are the areas of the laser beam in the gain and absorber media, $N_{g,a}$ are the population differences for the gain medium and saturable absorber, respectively, and γ_c is the resonator cavity photon decay rate. $\gamma = 1 + g_2/g_1$, where $g_{1,2}$ are the lower, upper laser level degeneracies (for Er:glass, at room temperature, $\gamma \approx 2$). The lifetime of the laser and absorber excited-states have been assumed to be long compared to the Q-switch pulse duration. The absorber is assumed to be 3-level (i.e., the upper level of the absorption transition quickly decays to a second excited-state level and there is no excited-state absorption).

In order for an absorber to Q-switch a laser, the absorber cross-section must satisfy the following:[4,5]

$$\sigma_a > \frac{\gamma A_a}{A_g} \sigma_g \qquad (4)$$

We are only considering slowly-relaxing absorbers here, i.e. the excited-state decay time is long compared with the Q-switch pulse of the laser. If $\sigma_a \approx \gamma\sigma_g$, then the laser beam must be concentrated to a smaller region in the Q-switch than in the gain medium (i.e. $A_a < A_g$), in order to achieve Q-switching. This is the case with Er^{3+}:CaF_2 and Er^{3+}:FAP where intracavity focussing is required. However, the cross-section of U^{4+}:SrF_2 is sufficiently high to allow Q-switching without intracavity focussing.

EXPERIMENTAL RESULTS

1543 nm Bleaching Measurements

The absorption spectrum for each of the Q-switch materials is shown in Figure 1. Values for the absorber cross-sections were obtained by measuring the saturation fluence for each of the Q-switch materials at 1543 nm using a Raman-shifted Nd:YAG laser. The pulsewidth of the Raman laser was about 15 nsec (short compared to the absorber lifetimes), and its spectral linewidth was less than 1 nanometer.

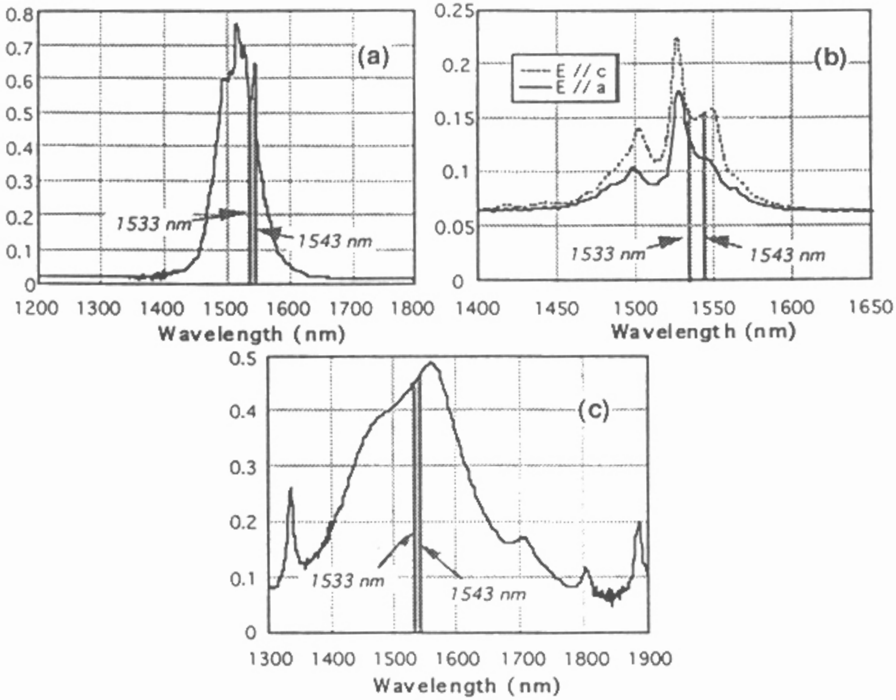

Figure 1. Room temperature absorption spectra of (a) Er^{3+}:CaF_2; (b) Er^{3+}:FAP; and (c) U^{4+}:SrF_2, near 1.53 μm. Vertical axes are optical density.

Transmittance (T) as a function of incident fluence, for a slowly-relaxing absorber with only saturable losses, is given by the modified Frantz-Nodvik equation:[6]

$$T = \frac{F_{sat}}{F_{in}} \ln \{ T_o [\exp (\frac{F_{in}}{F_{sat}}) - 1] + 1 \} \qquad (5)$$

where $F_{sat} = h\nu/\sigma_a$ is the saturation fluence, F_{in} is the incident fluence, and T_o is the small-signal transmittance. 1543 nm saturation fluence values of 9.2, 9.8, and 1.9 J/cm^2 were measured for Er^{3+}:CaF_2, Er^{3+}:FAP (**E//c**), and U^{4+}:SrF_2, respectively. The results for U^{4+}:SrF_2 are shown in Figure 2. The 1533 nm cross-sections were found to be approximatley 1.3×10^{-20}, 1.4×10^{-20}, and 6.9×10^{-20} cm^2 at 1533 nm, respectivley. These values were used in the theoretical modeling.

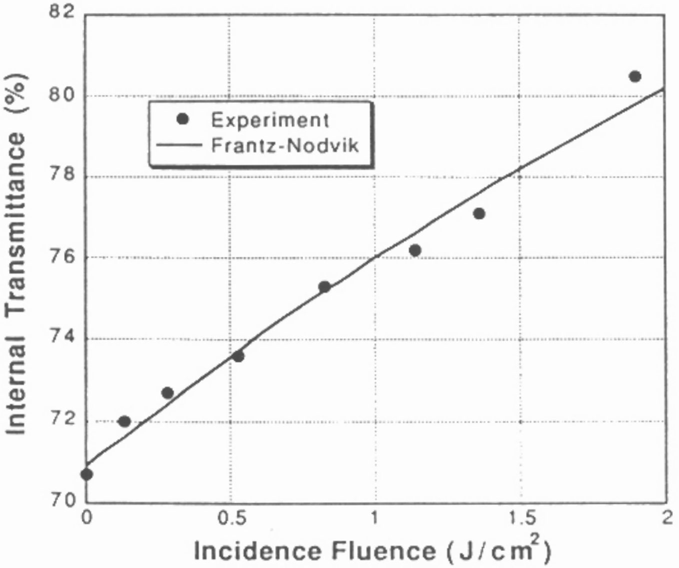

Figure 2. **Short-pulse bleaching of U^{4+}:SrF_2 at 1543 nm. Frantz-Nodvik saturation fluence = 1.86 J/cm^2.**

Er:Glass Q-Switch Experiments

All three materials produced Q-switch pulses near 1533 nm (spectrally narrower than the emission of the free-running Er:glass laser). Both Er:CaF_2 and Er:FAP required intracavity focussing to produce Q-switch pulses. This is as predicted by relation (4), using the measured absorber cross-sections and 0.8 x 10^{-20} cm^2 for the stimulated emission cross-section of Er:glass. U^{4+}:SrF_2 produced Q-switching without focussing, also as predicted by (4).

The cavity used for the Er:CaF_2 and Er:FAP Q-switches is shown in Figure 3a. The Q-switch was placed near the waist of the beam between the curved output mirror and the positive lens. The resonator cavity used for the U^{4+}:SrF_2 Q-switch was plane-parallel (Figure 3b). In all cases, we used a (flashlamp-pumped) 3 x 50 mm Kigre QE-7S Er:glass laser rod. The results obtained in saturable absorber Q-switching of Er:glass are summarized in Table I.

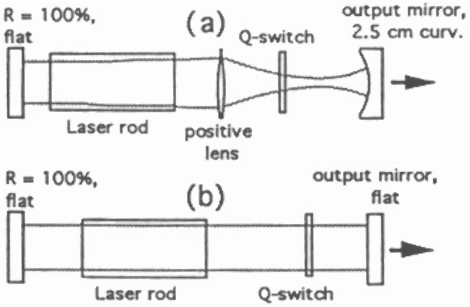

Figure 3. Resonator cavities used for (a) $Er:CaF_2$ and Er:FAP Q-switches, and (b) $U^{4+}:SrF_2$ Q-switch. Focal length of lens in (a) was +5 cm.

Table I. Summary of the saturable absorber Q-switch results.

Q-switch	Thickness (mm)	Output mirror Reflectivity (%)	Output Energy (mJ)	Threshold (J)	Q-switch Pulsewidth (nsec)
(2.0%) $Er:CaF_2$	1.0	94 (2.5 cm curv.)	11	51	69
(1%)Er:(1%)Yb: FAP (uncoated)	4.0	80 (2.5 cm curv.)	15	135	43
(1%)Er:(1%)Yb: FAP (AR-coated)	5.0	94 (2.5 cm curv.)	27	44	47
$U^{4+}:SrF_2$	2.7	94 (flat)	3	20	60

Equations (1) through (3) were numerically solved using a Runge-Kutta routine. For the case of $U^{4+}:SrF_2$, we obtained good agreement between theory and experiment, using the measured cross-section of 6.9×10^{-20} cm^2 and assuming 5% (nonsaturable) cavity losses. For $Er:CaF_2$ and Er:FAP, the pulse width and shape were correctly predicted using reasonable cavity losses in the theoretical model. However, the pulse energy was generally lower than predicted. We are still investigating this discrepancy. Er:FAP usually produced a Q-switched pulse followed by lower power, free-running spikes. The $Er:CaF_2$ Q-switch did not exhibit any free-running even though its lifetime is longer than Er:FAP.

The saturable absorber Q-switches could be damaged in Q-switching operation. By adjustment of the laser resonator, satisfactory Q-switched operation of the Er:glass laser could be obtained without damage to the Q-switch. An example of the results obtained when the saturable absorber Q-switch is damaged is shown in Figure 4. The sharp cut-off of the pulse, we believe, is due to the onset of damage which blocks the laser beam.

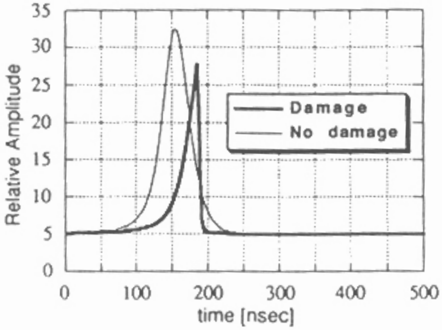

Figure 4. Er:FAP Q-switch pulses with and without the occurrence of Q-switch damage.

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