Passive Q switching of the Er^{3+}:$Y_3Al_5O_{12}$ laser at 1.64 μm

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Saturable-absorber Q switching of an erbium-doped $Y_3Al_5O_{12}$ (YAG) laser at 1.64 μm using U^{2+}:SrF_2 and U^{2+}:CaF_2 was demonstrated. The Er:YAG was longitudinally pumped using a free-running 1.534 μm Er:glass laser. Q switched 1.64 μm pulses of 1.7 mJ and 25 ns pulse widths were obtained. © *1995 American Institute of Physics.*

Q-switched, eyesafe lasers have important applications in remote sensing, lidar, and eyesafe rangefinding. Saturable absorbers provide a simple, low-cost option for Q switching, but only in the last year have significant advances been made in passive Q-switch technology for this wavelength region. Several new saturable absorber Q switches for the 1.5 μm Er^{3+}:glass laser have recently been reported,[1–3] and we now show that some of these Q-switch materials can be used with the 1.64 μm Er:YAG laser. Excellent results are expected with cobalt-doped garnet crystal Q switches,[3] where preliminary trials have been favorable.

In some respects Er:YAG is advantageous in comparison to Er:glass. The 1.64 μm Er:YAG laser is a quasi-four-level laser because of the large splitting of the ground-state ($^4I_{15/2}$) manifold, whereas Er:glass is a three-level laser. Er:YAG has a thermal diffusivity of over an order of magnitude larger than that of glass.[4] Er:YAG could be a good candidate for applications requiring high average power.

The Er:YAG laser crystal was longitudinally pumped with a free-running 1.534 μm Er:glass laser. This procedure[5] directly populates the upper energy level manifold ($^4I_{13/2}$) of the 1.64 μm laser transition and, therefore, minimizes the amount of heat deposited in the YAG crystal. The Er:YAG crystal was grown at the Crystal Products Division of Union Carbide[6] and fabricated into a 0.25 in.×3 in. rod. The crystal was doped with 15% of ytterbium as well as 0.3% of erbium, by atomic weight. The ytterbium ions did not affect the 1.64 μm laser, since only the erbium upper laser level was pumped (this crystal is herein named simply Er:YAG). The 1.64 μm resonator configuration used is shown in Fig. 1. The 1.534 μm Er:glass laser beam was focused inside the Er:YAG rod with a +15 cm focal length lens to obtain an ~1 mm diam beam waist. The folded resonator cavity of Fig. 1 was chosen in order to prevent pumping of the passive Q switch by the Er:glass laser at 1.534 μm. A longitudinally pumped, unfolded arrangement could be designed by using a normal incidence dichroic coating to reduce or eliminate 1.5 μm pumping of the saturable absorber. The intracavity +5 cm focal length lens concentrated the 1.64 μm light in the Q-switch crystal. A 97% reflective output mirror at 1.64 μm was used.

Two different Q-switch materials (divalent uranium ions in SrF_2 and CaF_2) were used. Our identification of the U^{2+} ion in these crystals was made according to Hargreaves.[7,8] The Er:YAG laser wavelength is well off the peak of the absorption for both materials (see Fig. 2). A 2.5 mm thick U^{2+}:SrF_2 Q switch produced pulses with full width at half-maximum (FWHM) pulse widths of 88–140 ns [Fig. 3(a)]. The internal (saturable) small-signal transmittance of this Q switch was 92% at 1.64 μm.

The best results were obtained with a 4.0 mm thick U^{2+}:CaF_2 which produced 1.7 mJ, 25 ns (FWHM) pulses [Fig. 3(b)]. The internal transmittance of the U:CaF_2 Q-switch was 83%. A U:SrF_2 Q-switch with a similar transmittance is expected to produce the same or even better results than those with the U:CaF_2 Q-switch. However, only a 2.5 mm thick U:SrF_2 crystal are available.

Figure 4 shows the temporal relationship between the Er:glass pump laser pulse and the output pulse (both Q-switched and free-running) of the Er:YAG laser with the U:CaF_2 Q-switch. These pulses were recorded using a Judson (J16 series) germanium photodiode detector and a Tektronix TDS-540 digital oscilloscope. The free-running Er:YAG output was observed with the U:CaF_2 Q switch removed, but with the same Er:glass laser input energy.

The efficiency of the U:CaF_2 Q-switched Er:YAG output relative to the free-running Er:YAG output was about 30%. However, the pump-to-laser output efficiency (1.64 μm output divided by absorbed 1.534 μm pump energy) was only about 1.5%, for the free-running Er:YAG. There are several factors which may account for this observation, including:

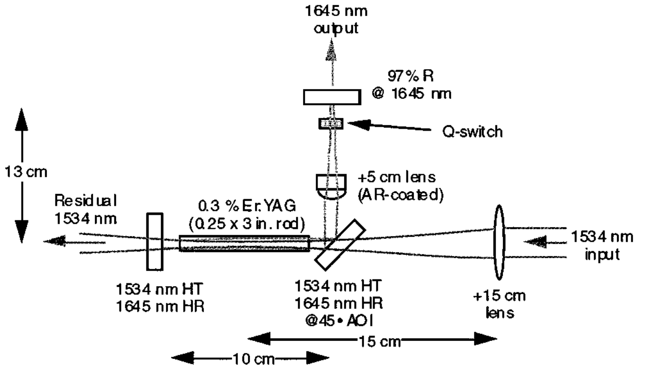

FIG. 1. Er:YAG laser resonator.

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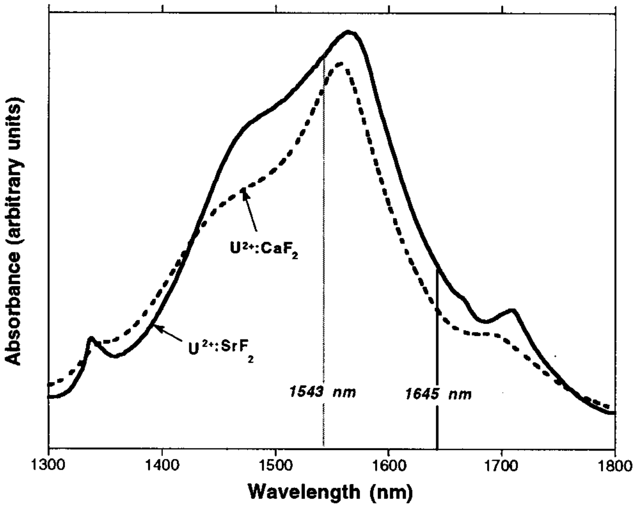


FIG. 2. Absorption spectra of U^{2+}:CaF_2 and U^{2+}:SrF_2 near 1.64 μm.

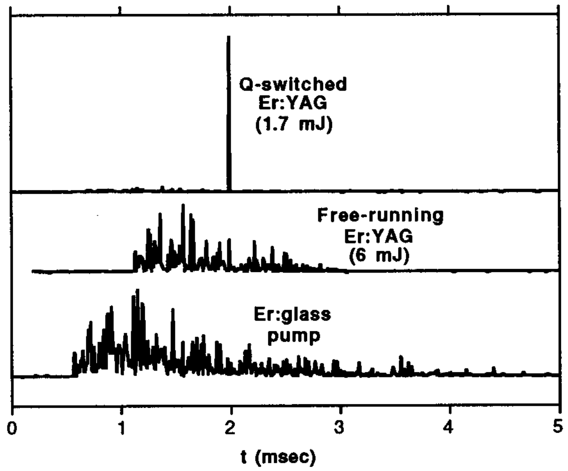


FIG. 4. Temporal relationship between Er:glass (1.534 μm) pump and Er:YAG (1.64 μm) output. Both Q-switched (with U:CaF_2) and free-running (Q-switch removed) Er:YAG pulses are shown.

(1) a poor spatial overlap between the pump beam and the Er:YAG resonator modes, and (2) large surface-reflection losses, resulting from uncoated components in the resonator. The Er:YAG rod, and the uranium-doped Q switches were uncoated.

Prior experiments using a 1 cm long, 0.5% concentration Er:YAG crystal (pumped with Er:glass) with an output coupling of 5%, have yielded a threshold absorbed 1.5 μm energy of 10 mJ, and a corresponding 1.64 μm slope efficiency of 40%.[5] The same 1 cm crystal did not produce lasing in the present cavity with the passive Q switches probably because of insufficient gain. We anticipate that with a properly designed system, similar efficiencies could be achieved with a passively Q-switched Er:YAG laser.

The rate equations for a slowly relaxing saturable absorber Q switch are given in Ref. 2. Laser threshold (at a time t_0 prior to the Q-switched photon pulse) is achieved when the gain just exceeds the losses (including those of the saturable absorber). At this point, the rate of growth in photon population $(d\phi/dt)_{t=t_0}$ is small. For Q switching to occur, the absorber must then saturate faster than the gain. This condition is given mathematically by:[9]

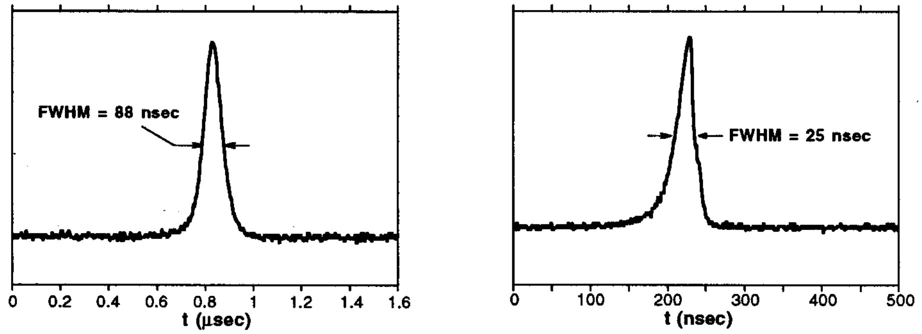
$$\left.\frac{d^2\phi}{dt^2}\right|_{t=t_0} > 0, \tag{1}$$

where ϕ is the (time-dependent) photon population of the resonator cavity. Using the inequality (1), and Eqs. (2)–(4) from Ref. 2, it is relatively straightforward to derive the following condition for passive Q switching:

$$\sigma_a > \gamma \frac{A_a}{A_g} \sigma_g , \tag{2}$$

where σ_a, σ_g are the effective Q-switch absorption and laser stimulated-emission cross sections, and A_a, A_g are the transverse laser beam areas in the Q switch and laser-active crystals, respectively. The constant γ is equal to $1 + g_2/g_1$ for a three-level laser, where g_2, g_1 are the upper, lower laser energy level degeneracies. In the case of a quasi-four-level laser, such as Er:YAG, $\gamma \approx 1$.

We have measured room-temperature $^5I_5$ fluorescence ($\sim$2.6 μm) lifetimes of 25 and 5 μs for U^{2+}:SrF_2 and U^{2+}:CaF_2. Assuming that all of the U^{2+} ions pumped by the 1.64 μm, decay back to the $^5I_5$ metastable level, then the



(a) **(b)**

FIG. 3. Sample Er:YAG Q-switched output pulses with (a) a 2.5 mm thick U^{2+}:SrF_2 Q switch, and (b) a 4.0 mm thick U^{2+}:CaF_2 Q switch.

absorption relaxation lifetime is at least as long as the fluorescence lifetime, and the slowly relaxing absorber theory applies.

The absorption cross sections of U^{2+}:SrF_2 and U^{2+}:CaF_2 were obtained from saturation fluence measurements.[2] Both materials have the same cross section at 1543 nm (7×10^{-20} cm^2), within experimental error. Assuming a homogeneous broadening of the U^{2+} absorption feature at 1.5 μm, the cross section should vary with wavelength proportionately with the measured absorption coefficient. Using the absorption spectra from Fig. 2, and the measured cross section at 1543 nm, the cross sections at 1.64 μm should be about 3.2 and 2.7×10^{-20} cm^2, respectively, for U^{2+}:SrF_2 and U^{2+}:CaF_2. The stimulated emission cross section[5] for the 1.64 μm Er:YAG laser transition is about 1.9×10^{-20} cm^2. The condition (2) implies that with $A_a/A_g=1$, Q switching is barely feasible without intracavity focusing since $\sigma_a/\sigma_g\approx1.5$. For efficient Q switching, focusing is required such that $A_g \gg A_a$.

In conclusion, we have shown that efficient passive Q switching can be obtained for the 1.64 μm Er:YAG laser using U^{2+}:SrF_2 and U^{2+}:CaF_2 saturable absorbers.

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