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Franck Falcoz, F. Kerboull, Frédéric Druon, François Balembois, Patrick Georges, Alain Brun

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F. Falcoz, F. Kerboull, F. Druon, F. Balembois, P. Georges, and A. Brun

Institut d'Optique Théorique et Appliquée, Unité de Recherche Associée au Centre National de la Recherche Scientifique No. 14, Université Paris-Sud, BP 147 91403 Orsay Cedex, France

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We measured small-signal gain in a cw diode-pumped Cr:LiSAF and showed that upconversion and thermal quenching of fluorescence strongly limit small-signal gain. Then we optimized the gain in a Cr:LiSAF laser pumped by two 400-mW red diodes. In Q-switched operation, this laser produced tunable nanosecond pulses between 800 and 900 nm. At 850 nm, we obtained 230-ns pulses with an energy of 6.5 μJ at a repetition rate of 10 kHz. © 1996 Optical Society of America

The fluorescence lifetime of Cr:LiSAF (67 μs) makes this crystal convenient for the development of a Q-switched cw diode-pumped laser operating at a high repetition rate (greater than 10 kHz). For a given pump power, small-signal gain is an important parameter for laser design because it determines the pulse duration and the extraction of the energy stored in the gain medium. However, because of the physical properties of Cr:LiSAF, small-signal gain is not a linear function of the pump power[1]: the upconversion process[2,3] and thermal quenching of fluorescence[4] limit the excited-state population at high pump levels. The gain properties of Cr:LiSAF have been extensively studied[1–3,5] under pulsed pumping (flash-lamp or pulsed laser diode), but, to our knowledge, no study has been carried out under cw pumping.

In this Letter we present a simple method of measuring the small-signal gain in a Cr:LiSAF crystal. We use this method to measure the small-signal gain of a 3%-doped crystal pumped by a krypton-ion laser. With a simple theoretical model, we point out small-signal gain limitations as the pump power increases. Then we describe experimental optimization of small-signal gain in a diode-pumped Cr:LiSAF laser. Finally, we describe the performances of this laser in Q-switched operation.

The small-signal gain G_0 per double pass in a gain medium is defined by $G_0 = I_{\text{out}}/I_{\text{in}}$, where I_{in} and I_{out} are the intensity before and after one round trip in the laser rod, respectively. Different methods have been tested for gain measurement. The simplest is to probe the gain medium with another laser.[1] But under cw pumping, the gain is too low for this method to be used. A second possibility is to measure the relaxation oscillation frequency, which depends on the gain.[6] However, this method requires a constant fluorescence lifetime all over the crystal. This is not the case for Cr:LiSAF crystals, whose lifetime depends on the spatial distribution of temperature.[4] In our case, we investigated the evolution of laser threshold as a function of intracavity losses.

We introduced a glass plate into the cavity at a variable incidence angle θ. As the laser polarization is in the incidence plane, we can define the reflection coefficient for one round trip in the cavity $R(\theta)$ as

$$R(\theta) = R_{\text{pl}}\left[1 - \left(\frac{n\cos\theta - \cos\theta'}{n\cos\theta + \cos\theta'}\right)^2\right]^4,$$
$$\sin\theta' = \sin\theta/n\,. \quad (1)$$

R_{pl} is the reflection coefficient for one round trip in the cavity without the rotating plate (passive losses), and n is the refractive index of the plate. At threshold, the laser starts oscillating, so we can write

$$G_0 R(\theta) = 1\,. \quad (2)$$

Thus we can deduce the value of G_0 when we know θ, n, and R_{pl}.

The experimental setup is shown in Fig. 1. We used a three-mirror cavity defined by a plano–Brewster crystal (3% doped) (M_1), a highly reflective concave mirror (M_2), and a plane output coupler (M_3). The rotating plate was a 5-mm-thick glass plate ($n = 1.446$) and was introduced near M_3. Thus the cavity losses could be continuously changed without any misalignment of the cavity (unlike when different output couplers are used). To determine R_{pl}, we measured pump power at threshold for different output couplers with low transmission (0.1%, 1%, and 2%). As the threshold was low (less than 60 mW), we could assume that it was a linear function of output coupling, and we could apply Findlay–Clay calculations.[7] We found that R_{pl} was equal to 0.993, in good agreement with the mirror's reflectivities and with the low scattering losses inside the crystal. We estimated the absolute accuracy of our method to be 0.005 for the G_0 value.

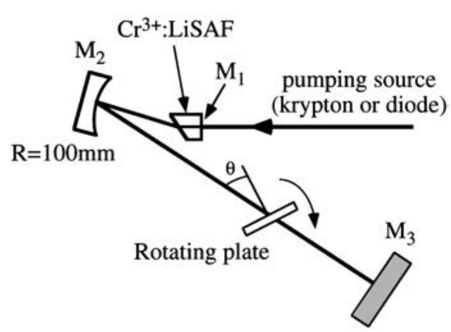

Fig. 1. Experimental setup for small-signal gain measurement.

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We first investigated which physical effects limit small-signal gain under cw pumping. We used a krypton-ion laser because its circular beam profile makes theoretical calculations easier than with a laser diode. The laser operated in cw regime up to 450 mW of absorbed pump power. Figure 2 shows experimental measurements of small-signal gain: We observed that the gain reached a maximum of 1.16 and decreased with greater than 300 mW of absorbed pump power. We simultaneously calculated small-signal gain by using the formalism of Alfrey.[8] As no gain limitations were introduced into the calculations, we obtained a theoretical gain much greater than the gain from the experimental results (Fig. 2). However, as we introduced both upconversion and thermal quenching, the theoretical curve could fit the experimental measurements. For the calculations, we took an upconversion constant equal to $6.5 \times 10^{-16}\ \mathrm{cm}^3\ \mathrm{s}^{-1}$, which corresponds to the value given by Payne *et al.*[5] for a 3%-doped Cr:LiSAF crystal. To evaluate the relative influence of upconversion and thermal quenching, we operated the krypton-ion laser in the quasi-cw regime. The maximum power during the pumping window remained at 450 mW, and the duty cycle was fixed at 1/6 so that the average absorbed pump power did not exceed 75 mW. At this power level, the temperature inside the crystal was less than 40 °C (based on temperature calculations given in Ref. 9), and the fluorescence lifetime still remained longer than 57 μs (compared with 67 μs at 0 °C). In this case, we could assume that the gain was limited mainly by upconversion. In fact, gain calculations fitted the experimental results well when only upconversion was taken into account (Fig. 2). Thus theoretical and experimental investigations with the krypton-ion laser have shown that the main limitation of small-signal gain is upconversion, whereas the combined effects of thermal quenching and upconversion are responsible for the gain's decreasing with greater than 300 mW of absorbed pump power.

Next we tested small-signal gain by pumping the Cr:LiSAF crystal with a laser diode provided by Applied Optronics and emitting 400 mW of power cw at 670 nm. The dimensions of the emitting zone were 1 μm by 100 μm. The pumping scheme was similar to those previously described.[10] We imaged the emitting zone inside the crystal by using the following system: the beam was first collimated with a high-numerical-aperture objective; then afocal systems reshaped the beam and a second objective focused it inside the crystal (Fig. 3). We tried two pumping configurations with one or two afocal systems. Afocal #1 (Fig. 3) was used to reduce the image size in the plane of the junction, whereas Afocal #2 magnified the image size in a perpendicular direction. With only Afocal #1, we measured a spot size of 40 μm by 10 μm at the focus point. By adding Afocal #2, we measured a spot size of 40 μm by 40 μm. Figure 4 shows the results obtained with the two configurations. Maximum gain value was 1.06 with Afocal #1 and 1.08 with Afocals #1 and #2. The pumping area at the focus point was four times greater in the second configuration than in the first one, leading to an absorbed pump power density that was four times lower. Both excited-state population density and temperature at the focus point were lower, so upconversion and quenching were not so important. However, at 300 mW of absorbed pump power (cw), G_0 was 1.08 under diode pumping and 1.16 under kyrpton pumping. The difference is due to better overlapping between pump and cavity beams in the case of krypton pumping.

To increase the pump power, we used two diodes of 400 mW. We compared two pumping configurations in terms of gain. First, we combined the two diodes by polarization and observed a small-signal gain decrease to 1.06 for a total absorbed pump power of 600 mW. This value of G_0 was less than the value

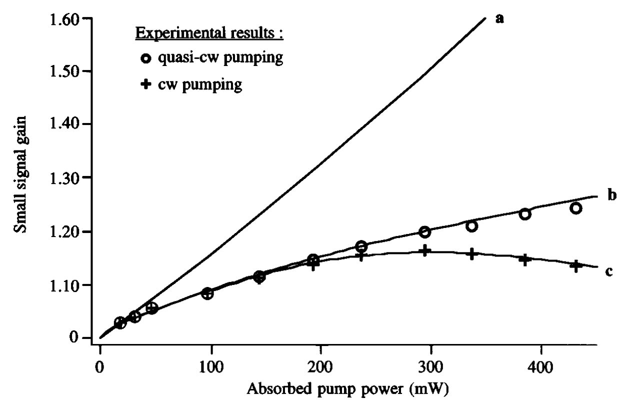

Fig. 2. Small-signal gain evolution as a function of the absorbed pump power under krypton pumping. Curves a, b, and c are for calculated small-signal gain without any limitations, with only the upconversion process, and with upconversion and thermal quenching of fluorescence, respectively.

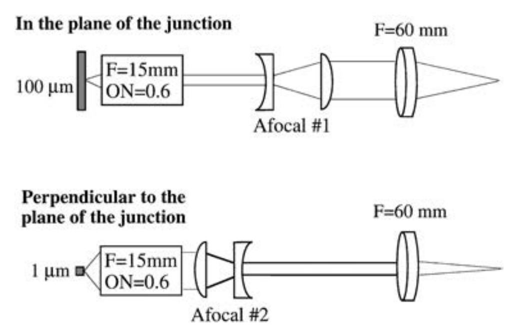

Fig. 3. Pumping scheme in the case of one laser diode. F, focal length; ON, numerical aperture.

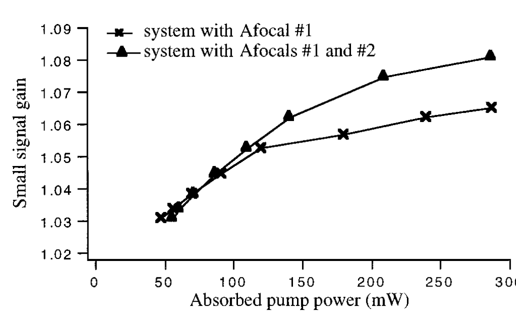

Fig. 4. Small-signal gain evolution as a function of the absorbed pump power under diode pumping.

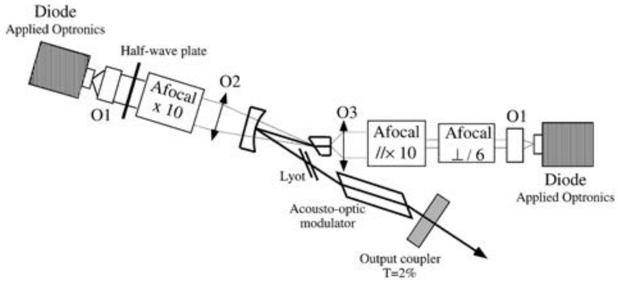

Fig. 5. Experimental setup for a Cr:LiSAF laser pumped on both sides by two laser diodes. O1–O3, objectives.

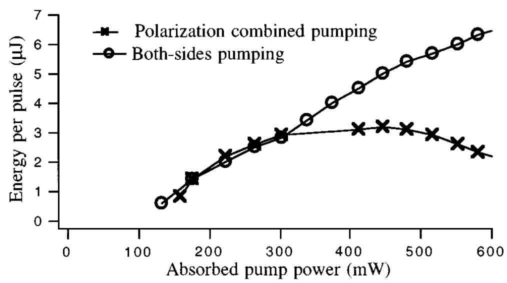

Fig. 6. Energy per pulse as a function of the pump power in Q-switched operation.

of 1.08 obtained with only one diode, showing the effects of upconversion and quenching as the pump power increased (see Fig. 2). Second, we pumped the crystal on both sides. Figure 5 shows the experimental setup. On the plane face of the crystal, we used the pumping system described above with two afocal system. On the Brewester-angled face, gain optimization led to a system with only one afocal system because we took advantage of 1.4 magnification of the air–glass interface in the incidence plane. The junction plane was perpendicular to the plane of the cavity, and the polarization of the pump beam was adjusted with a half-wave plate to maximize the absorption inside the crystal. We obtained a gain of 1.11 for 600 mW of absorbed pump power, compared with 1.06 when the two diodes are combined by polarization. In the case of pumping on both sides of the crystal, absorbed pump power was better distributed in the crystal, leading to less upconversion and fewer quenching problems.

To achieve Q-switched operation, we added an acousto-optic modulator inside the cavity. Figure 6 shows the energy per pulse as a function of absorbed pump power for pumping on both sides and polarization-combined pumping configurations. We could obtain twice as much energy (6.5 instead of 3 μJ) per pulse by choosing pumping on both sides. In this configuration, the pulse duration was 230 ns. No decrease of energy per pulse was observed until the repetition rate was 10 kHz. The pulse energy remained greater than 5 μJ between 820 and 900 nm. We also increased the repetition rate to 80 kHz and observed that the pulse energy remained greater than 2 μJ.

Small-signal gain limitations are bound with absorbed pump power density. To reduce it, we studied a Cr:LiSAF crystal with a longer absorption length (1.5%-doped). We obtained similar performance in terms of gain and energy per pulse. For this crystal, upconversion and thermal quenching were less important, but overlapping between pump and cavity beams was worse.

In conclusion, small-signal gain measurements under krypton pumping have allowed us to prove that the upconversion process and thermal quenching of fluorescence are the most important gain limitations in a 3%-doped Cr:LiSAF crystal. The optimization of small-signal gain under cw diode pumping led us to circularize the pump spot at the focus point inside the crystal and to distribute the absorbed pump power by pumping the crystal on both sides. Owing to small-signal gain measurements, we succeeded in the realization of an efficient Q-switched diode-pumped Cr:LiSAF laser operating at a high repetition rate (up to 80 kHz), producing tunable nanosecond pulses with an energy of up to 6.5 μJ. This method of small-signal gain measurements and optimization could be used for regenerative amplifiers based on diode-pumped Cr:LiSAF crystals.

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