

30 W Cr:LiSrAlF₆ flashlamp-pumped pulsed laser

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We report the performance of a flashlamp-pumped Cr:LiSrAlF₆ (Cr:LiSAF) laser developed and built by us. The pumping cavity incorporates filters that select the flashlamps' emission spectrum to match the absorption bands of the gain medium, allowing control of the amount of nonradiative decay heat contribution of the optical cycle, minimizing thermal effects on the laser operation. The laser generated 2 J pulses at 15 Hz, resulting in 30 W of average power, the highest power extracted from a Cr:LiSAF rod laser to our knowledge. We were able to conclude that the laser efficiency is affected by resonator configuration changes due to thermal lens effects, and not to thermal quenching of the Cr:LiSAF luminescence. © 2006 Optical Society of America

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Cr:LiSAF (Cr³⁺:LiSrAlF₆) single crystals are very attractive laser media because of their spectroscopic properties,¹ such as a long lifetime of the upper laser level ($\sim 67 \mu\text{s}$) at room temperature,² three broad absorption bands,² and a wide emission band ranging from 650 to 1050 nm. Laser action was demonstrated under several pumping schemes²⁻⁵ in pulsed and cw⁶ regimes. Pulse durations ranging from hundreds of microseconds under free-running pulsed excitation down to nanoseconds in Q-switching and few femtoseconds in mode-locking regimes⁷ were achieved.

Flashlamp-pumped Cr:LiSAF lasers^{3,8-10} have been developed that reach pulse energies as high as 8.8 J, and flashlamp-pumped ultrashort pulse amplifiers¹⁰⁻¹³ have reached peak powers up to 8.5 TW. Because of the LiSAF host's¹⁴ poor thermal properties, the operation repetition rate of these lasers and amplifiers were always confined to be under 12 Hz.⁸ The low thermal conductivity of LiSAF leads to crystal cracking due to thermally induced stress, and fracture was observed¹⁵ at 18 Hz for a gain medium in the shape of a rod. Also, the Cr:LiSAF laser transition is strongly temperature dependent owing to thermal quenching.¹⁶ To avoid these detrimental effects of accumulated heat, flashlamp-pumped Cr:LiSAF lasers have been restricted to operating at low repetition rates. In the early 1990s Shimada *et al.*⁸ reported the highest repetition rate and power for a Cr:LiSAF laser to be 4.5 W at 12 Hz, and Perry *et al.*¹⁷ reported 10 Hz as the highest amplifier repetition rate. In 2002 Klimek and Mandl⁹ extracted 8.8 J pulses from a Cr:LiSAF slab laser that allowed better heat extraction, but at 5 Hz repetition rate.

Recently we proposed a different approach in designing a two-flashlamp pumping cavity for a Cr:LiSAF rod, aiming to minimize the thermal load on the gain medium. The main heat source for a Cr:LiSAF crystal is the Stokes shift from the three absorption bands centered at 290, 450, and 650 nm to the emission band at 850 nm; for a photon absorbed by the 290 nm band resulting in an emitted photon at 850 nm, about 65% of its energy ($\sim 2.8 \text{ eV}$) is converted into heat, and for photons absorbed by the 430 and 650 nm bands, these portions are 50%

($\sim 1.4 \text{ eV}$) and 24% ($\sim 0.5 \text{ eV}$), respectively. In our design, intracavity optical filters (filter set 1 shown in Fig. 1) were placed between the flashlamps and the rod, allowing only the 650 nm absorption band to be pumped, minimizing the Stokes-shift-generated heat. Also, the Xe flashlamps and power sources were chosen to produce pulse durations matching the Cr:LiSAF lifetime and to have a blackbody emission temperature around 8000 K (displacing their emission spectra to the visible region), increasing the pump efficiency. Water at 11°C was used as coolant, maintaining the Cr:LiSAF crystal near room temperature. Details of the cavity design and laser operation with filter set 1 are given in our previous work,¹⁸ and the laser allowed extraction of 20 W of average power at a 30 Hz repetition rate without significant thermal effects at the highest pumping energy and repetition rates.

We report here the results obtained for laser operation when pumping the Cr:LiSAF higher energy absorption bands for the same configuration used in our earlier work. For this purpose we replaced the intracavity filters (filter set 1) either with filters cut from Schott GG385 glass (filter set 2) or from common glass (filter set 3), whose transmission spectra are shown in Fig. 1. Defining the pumping efficiency as

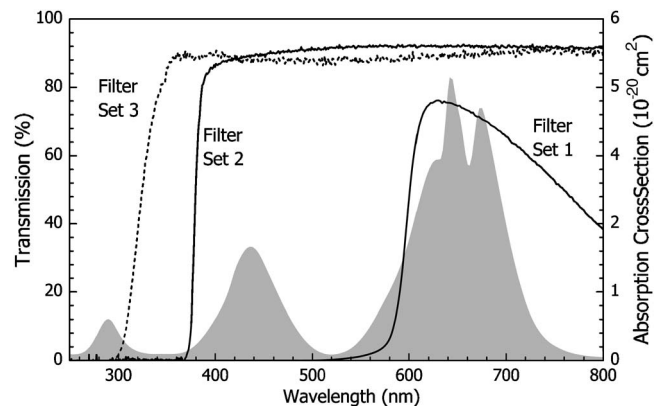


Fig. 1. Transmission spectra of the intracavity filters and Cr:LiSAF π -polarization absorption spectrum (shaded, right-hand scale), showing the selection of the pumping bands.

the ratio of the energy absorbed by the crystal by the total pumping energy, filter sets 2 and 3 result in a higher efficiency than does filter set 1.

Following the procedures described in our preceding work,¹⁸ the laser output pulse energy (E_{pulse}) was measured as a function of the total electric pumping energy (E_{pump}) to a maximum energy of 100 J, at a 2 Hz repetition rate, for various output couplers reflectivities (R_{OC}), for either filter set 2 or filter set 3 placed inside the cavity; the percent slope efficiencies ($100 \times \partial E_{\text{pulse}} / \partial E_{\text{pump}}$) and laser threshold pumping energies (E_{th}) were obtained, for each output coupler and intracavity filter set, from linear fits to the measured data. The maximum slope efficiency obtained for filter sets 2 and 3 were $(3.14 \pm 0.02)\%$ for the $R_{\text{OC}}=71.5\%$ mirror and $(3.39 \pm 0.02)\%$ for the $R_{\text{OC}}=68.6\%$ mirror, respectively. The maximum overall efficiency ($100 \times E_{\text{pulse}} / E_{\text{pump}}$) obtained were 2.6% at 80 J pumping and $R_{\text{OC}}=84.9\%$ for filter set 2 and 2.81% at 84 J pumping and $R_{\text{OC}}=82.4\%$ for filter set 3. The highest pulse energy measured was (2.80 ± 0.01) J for $R_{\text{OC}}=74.7\%$ and 100 J pumping, for filter set 3, in $\sim 65 \mu\text{s}$ (FWHM) pulses. The obtained laser threshold pumping energies were used to determine the resonator total losses L , through a Findlay–Clay analysis.¹⁹ These losses amount to $(12.3 \pm 2.2)\%$ for filter set 2 and $(16.4 \pm 2.9)\%$ for filter set 3, higher than the $(4.8 \pm 0.9)\%$ value calculated for filter set 1.¹⁸ These results show that the resonator losses are not purely passive, depending on which bands are used for pumping, and the increase observed is probably due to laser excited state absorption¹⁵ arising from the higher energy levels directly populated by pumping on the 430 and 290 nm bands. The threshold gain, $g_{\text{th}}l$ (g_{th} being the small-signal threshold gain and l the gain medium length), and threshold gain per pass, $G_{\text{th}} = \exp(g_{\text{th}}l)$, were then calculated for each filter set and output coupler configuration by²⁰

$$g_{\text{th}}l = \frac{1}{2}[L - \ln(R_{\text{OC}})]. \quad (1)$$

Figure 2 shows, for each filter set, the threshold gain per pass and laser threshold pumping energy as functions of the output coupler reflectivities. In this figure we observe that, for each output coupler, the gain increases less than 10% from filter set 1 to the other sets, and this can be understood by referring to Eq. (1), which demonstrates that the gain depends only on the losses, which now include excited state absorption that depends on the bands pumped, and not on the pumping efficiency. The increase in the pumping efficiency can be seen in Fig. 2(b), which shows a decrease of ~ 3 times in the laser threshold pumping energy for filter sets 2 and 3. This decrease indicates that the flashlamps' emission peak is probably shifted to the blue spectral region, since when both the σ and the π Cr:LiSAF absorption spectra are considered² the 650 and 430 nm bands have approximately the same area, and consequently pumping the two bands should double the gain, once the threshold gain is proportional to the absorbed pumping energy.

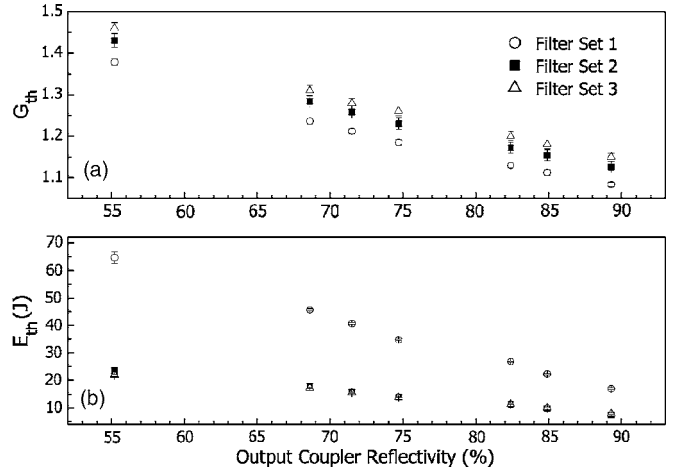


Fig. 2. (a) Threshold gain per pass and (b) laser threshold pumping energy as functions of the output coupler reflectivity for each filter set.

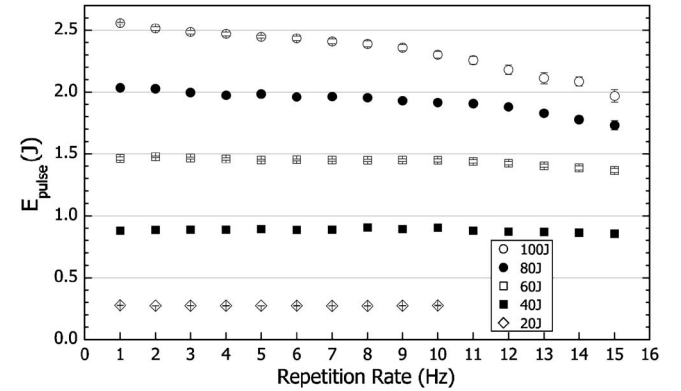


Fig. 3. Pulse energy dependence on the laser repetition rate for various pumping energies, filter set 2, and on $R_{\text{OC}}=84.9\%$ output coupler.

To investigate the influence of thermal effects on the laser's behavior, we used filter set 2, allowing pumping in the two lower energy bands, and the $R_{\text{OC}}=84.9\%$ output coupler and measured the pulse energy as the repetition rate increased; results are shown in Fig. 3. This graph shows that, for up to 40 J pumping, the pulse energy does not depend (within $\pm 3\%$) on the repetition rate, but for higher pumping energies the pulse energy decreases when the repetition rate increases. For the higher pumping energy (100 J) the laser pulse energy drops 23%, from (2.559 ± 0.007) J at 1 Hz to (1.969 ± 0.052) J at 15 Hz, indicating the presence of thermal effects, but nevertheless reaching a average power of (29.5 ± 0.8) W, the highest power, to our knowledge, to be extracted from a Cr:LiSAF rod. To verify if this energy drop results from thermal quenching of the Cr:LiSAF upper laser level, we simultaneously measured the temporal profile of the flashlamps' emission and of the Cr:LiSAF spontaneous emission and used the rate equation to fit the Cr:LiSAF lifetime to the spontaneous emission curve, as described in our earlier work.¹⁸ This was done for various pumping energies and repetition rates, and the results are shown in Fig. 4, where it can be seen that the Cr:LiSAF lifetime drops as the pumping energy increases but does

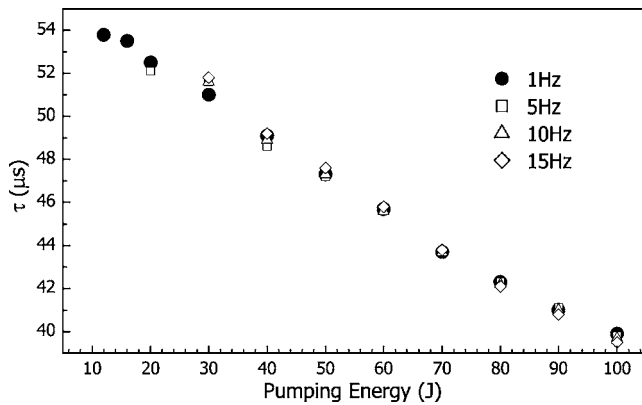


Fig. 4. Upper laser level transition lifetime as a function of the pumping energy, showing that the lifetime is not influenced by the repetition rate.

not depend on the repetition rate. These results indicate that the energy drop shown in Fig. 3 is not a consequence of thermal quenching of Cr:LiSAF luminescence and probably results from variations in the flashlamps' efficiency and a thermal lens effect that modify the resonator, lowering its overall efficiency. The lifetime decrease with the pumping energy rise most certainly results from excited state absorption processes that reduce the upper laser level population, and also from local heating caused by the Stokes shift, which is instantaneous (tens of picoseconds) and takes place in the Cr ion neighborhood. In the repetition rates investigated, this heat is removed by the cooling system, minimizing its accumulation between pulses, leaving enough heat to create a small thermal lens but not enough to quench the Cr ion lifetime.

The pulse energy dependence on the repetition rate measurements were repeated for the $R_{OC}=89.3\%$ mirror and filter set 3, which allows pumping in the wing of the 290 nm absorption band. At the higher pumping energy, this configuration produced (2.51 ± 0.02) J pulses at 1 Hz; however, the pulse energy decreased to (2.00 ± 0.05) J, over 20%, at an only 8 Hz repetition rate (16 W average power), which compares badly with only a 7% drop for filter set 2 at the same repetition rate (Fig. 3). This demonstrates that pumping on the 290 nm band increases the laser efficiency only slightly at low repetition rates, compared with pumping in the 650 and 430 nm bands, but thermal effects are much amplified at high repetition rates as a consequence of 2/3 of the pumping photon energy's being wasted in Stokes-shift-generated heat.

In summary, we developed and built a Cr:LiSAF pumping cavity that allowed laser operation in various regimes depending on the intracavity filters used. These regimes made possible the operation of the laser at repetition rates up to 30 Hz,¹⁸ or at ener-

gies up to 2.8 J and peak power in excess of 40 kW. We demonstrated laser operation at 30 W of average power, the highest reported for a Cr:LiSAF rod gain medium. Additionally, we studied the gain medium behavior as a function of the pumping repetition rate, demonstrated the existence of thermal effects due to Stokes shift that decrease the laser overall efficiency and lower the pulse energy, but ruled out Cr:LiSAF luminescence quenching as the cause of this drop. Pumping the Cr:LiSAF 290 nm absorption band increases the laser energy by $\sim 10\%$ compared with pumping only the other two bands, but the trade-off is a greater efficiency drop at higher repetition rates.

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