Development of a Lamp-Pumped Cr:LiSAF laser operating at 30 Hz

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Abstract

Cr\(^{3+}\):LiSrAlF\(_6\) crystals area a very interesting laser medium due to its spectroscopic characteristics, presenting a broad emission band in the near infrared and being able to be pumped either by flashlamp or by diodes. Up to now, its limitation is mostly due to its poor thermal properties that limit the laser performance either in the repetition rate in pulsed system or output power in CW systems. We have designed and constructed a flashlamp pumped laser using a standard rod pumping cavity that avoided most of the heat generated in the pumping process and allowed the operation in a fairly high repetition rate of 30 Hz with a high average power of 20 W in a conservative operation mode.

Introduction

Single crystals of Cr:LiSAF (Cr\(^{3+}\):LiSrAlF\(_6\)) show very attractive optical spectroscopic properties\(^1\) for a potential laser medium, such as a long lifetime of the upper laser level (~67 \(\mu\)s) at room temperature\(^2\), three broad absorption bands\(^2\) and a wide emission band ranging from 650 nm to 1050 nm. Laser action was demonstrated under several pumping schemes\(^3\), \(^4\), \(^5\), particularly in CW\(^6\) and pulsed 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 regime\(^7\) were achieved.

Flashlamp-pumped Cr:LiSAF tunable lasers\(^8\), \(^9\), \(^10\), \(^11\), \(^12\), \(^13\), \(^14\) have been developed reaching pulse energies up to 8.8 J, and flashlamp pumped ultrashort pulse amplifiers\(^11\), \(^12\), \(^13\), \(^14\) reached peak powers up to 8.5 TW. Due to the poor thermal properties of the LiSAF host\(^15\), the operation repetition rate of these lasers/amplifiers were always confined either to the single pulse regime or up to 12 Hz\(^8\). The low thermal conductivity leads to crystal cracking due to thermally induced stress, and in the case of a gain medium in the shape of a rod, fracture was observed at 18 Hz\(^16\). Besides the thermal induced stress that leads to fracture, the lifetime of the Cr:LiSAF laser transition is strongly temperature dependent, dropping from ~67 \(\mu\)s at room temperature to half this value at 69°C, due to thermal quenching\(^17\).

Under flashlamp pumping, the low LiSAF thermal conductivity prevents heat extraction from the laser medium, and if its temperature rises above ~25°C, the nonradiative decay generates more heat, what in turn increases the nonradiative decay rate, rapidly increasing the crystal temperature in a catastrophic process that reduces the energy storage capacity of the crystal and can lead to fracture.

In order to avoid thermal quenching and crystal fracture due to accumulated heat, flashlamp pumped Cr:LiSAF oscillators have been kept operating at low repetition rates. Shimada et al.\(^2\) reported the highest repetition rate and power on a Cr:LiSAF laser to be 4.5 W at 12 Hz, and Perry et al.\(^18\) reported the highest amplifier repetition rate to be 10 Hz. Alternatively, a slab geometry laser\(^9\) scheme requires small thickness of the gain medium, allowing for better heat extraction and therefore a lower stress in the gain medium and in this case the laser achieved pulse energies as high as 8.8 J, but at 5 Hz repetition rate.

Aiming to rise the repetition rate of flashlamp pumped Cr:LiSAF lasers and still keeping its gain and power, we propose a different approach that minimizes the crystal thermal load and temperature gradient by decreasing the heat reaching the gain medium and being generated inside it. This scheme allowed the laser operation at repetition rates as high as 30 Hz, with an average power of 20 W.

Experimental Setup

We developed a flashlamp pumped pumping cavity, aiming to minimize the rod thermal load and to increase the laser repetition rate. The rod has a 1.5mol% Cr doping, 101.6 mm of length and 6.35 mm of diameter, with Brewster angled faces. The cavity has two 4” arc-length, 7 mm bore, 450 torr Xenon flashlamps, each one independently fed by a power source capable of delivering up to 50 J in ~67 \(\mu\)s pulses. The pulse width was chosen in order to match the laser transition lifetime, consequently decreasing heat generation by pump energy that is lost to spontaneous emission. The cavity is a closed coupled one, with an alumina diffuse reflector, and cooled by deionized water at 11°C in turbulent flow regime. The humidity in the laboratory is kept under 40%, lowering the dew point, avoiding water condensation on the rod surfaces.
The temperature of the laser medium inside a pumping cavity is determined by how much energy is absorbed by the medium, and the amount of that energy that is not converted into light emission (spontaneous or stimulated), and how this excess energy is extracted. The main heat source for the Cr:LiSAF crystal is the Stokes-shift from the three absorption bands centered at 290 nm, 450 nm and 650 nm to the emission band at 850 nm. For a photon absorbed at the center of the 290 nm band resulting in an emitted photon at 850 nm, about 65% of its energy is converted into heat due to the Stokes-shift. For photons absorbed at the center of the 430 nm and 650 nm bands, these fractions are 50% and 24%, respectively. With the purpose of minimize the heat in the rod, optical filters were inserted into the pumping cavity between the rod and each one of the flashlamps, absorbing all light below 600 nm and above 700 nm. In this way, only the 650 nm band is excited, decreasing the Stokes-shift generated heat to only ~25% of the absorbed power. The pumping cavity was designed in a way that the optical filters divide it in three compartments, isolating the rod from the flashlamps, allowing independent coolant flow around each component. The cooling water flows around the rod, and then refrigerates the flashlamps. Thus, heat transfer from the flashlamps to the rod by the cooling water is avoided.

The optical resonator was built using a 1 m curvature radius concave High-Reflector mirror located 21 cm away from one rod end, and a plane output coupler located 12 cm from the other end of the rod, resulting in a stability product \( g_1 g_2 = 0.57 \) for an empty resonator. Plane output couplers with reflections ranging from 55% to 96% at 850 nm were used to characterize the laser performance.

Results and Discussions

The laser output pulse energy as a function of one of the flashlamps input energy, for eight different output coupler reflectivities \( R_{OC} \), is shown in figure 1. In Table 1 we present the total (2 flashlamps) pump energy threshold for laser action for each output coupler and the corresponding slope efficiencies. The maximum total measured efficiency is 0.65% for \( R_{OC} = 89.3\% \) and 100 J pumping energy. The laser emission is centered at 851 nm, with a bandwidth of 6.4 nm, and the pulse duration is 65 \( \mu \)s.

![Figure 1 - Cr:LiSAF laser slope efficiencies for various output couplers reflectivities (\( R_{OC} \)) along with linear fitted functions for each output coupler, as a function of the pump energy per flashlamp. For each \( R_{OC} \) data set, the two or three lower energy points were disregarded in the fitting due to the unstable laser oscillation near the threshold.](image)

<table>
<thead>
<tr>
<th>( R_{OC} ) (%)</th>
<th>(-\ln(R_{OC}))</th>
<th>( E_{in} ) (J)</th>
<th>Slope Eff. (%)</th>
<th>( g_d )</th>
</tr>
</thead>
<tbody>
<tr>
<td>95.9 ± 1.0</td>
<td>0.042 ± 0.010</td>
<td>8.68 ± 0.28</td>
<td>0.072 ± 0.001</td>
<td>0.045 ± 0.006</td>
</tr>
<tr>
<td>89.3 ± 0.4</td>
<td>0.113 ± 0.004</td>
<td>16.96 ± 0.24</td>
<td>0.818 ± 0.004</td>
<td>0.081 ± 0.005</td>
</tr>
<tr>
<td>84.9 ± 0.6</td>
<td>0.164 ± 0.007</td>
<td>22.28 ± 0.22</td>
<td>0.792 ± 0.004</td>
<td>0.106 ± 0.006</td>
</tr>
<tr>
<td>82.4 ± 0.5</td>
<td>0.193 ± 0.006</td>
<td>26.86 ± 0.22</td>
<td>0.848 ± 0.003</td>
<td>0.121 ± 0.005</td>
</tr>
<tr>
<td>74.7 ± 0.6</td>
<td>0.292 ± 0.008</td>
<td>34.80 ± 0.24</td>
<td>0.865 ± 0.003</td>
<td>0.170 ± 0.006</td>
</tr>
<tr>
<td>71.5 ± 0.5</td>
<td>0.335 ± 0.007</td>
<td>40.68 ± 0.34</td>
<td>0.799 ± 0.004</td>
<td>0.192 ± 0.006</td>
</tr>
<tr>
<td>68.6 ± 0.5</td>
<td>0.377 ± 0.007</td>
<td>45.64 ± 0.46</td>
<td>0.810 ± 0.005</td>
<td>0.212 ± 0.006</td>
</tr>
<tr>
<td>55.2 ± 0.5</td>
<td>0.594 ± 0.009</td>
<td>64.7 ± 2.0</td>
<td>0.66 ± 0.01</td>
<td>0.321 ± 0.006</td>
</tr>
</tbody>
</table>

Table 1. Values obtained from the fitted functions in Figure 1, for each output coupler.

From the data in the second and third columns in table 1, the resonator losses were determined through a Findlay-Clay analysis\(^1\). This analysis consists of fitting a line to the data of \(-\ln(R_{OC})\) as a function of the lasing threshold pump energy, and the resonator losses are given by the point where the line crosses the y-axis. The data fitted by the line is shown in figure 2, resulting in total resonator losses \( L \) with value \( L = (4.8 ± 0.9)\% \). It is then possible to calculate the threshold gain, given by\(^1\):
where \( g_t \) is the threshold small-signal gain and \( l \) is the rod length. From equation (1) the threshold gain can be determined for each output coupler and its values are shown in the fifth column of table 1.

\[
g_t l = \frac{1}{2} [L - \ln(R_{OC})] \quad (1)
\]

Figure 2 - Findlay-Clay analysis of the Laser. The fitted line crosses the y-axis at -0.048, providing the resonator losses.

Figure 3 shows the pulse energy dependence on the repetition rate. It can be seen that for 60 J pumping, the pulse energy is almost constant, varying 3% around its average value. For higher pump energies, a decrease of the pulse energy with increasing repetition rate is observed, and at 100 J and 30 Hz, this decrease is 8% of its value at 1 Hz. The measured pulse energy at 30 Hz is (660.4±9.4) mJ, resulting in 19.8 W of average power.

To investigate if this energy dropping is due to lifetime shortening as a consequence of rod heating and thermal quenching, the temporal shapes of the flashlamp and of the rod spontaneous emissions were measured with fast detectors and an averaging oscilloscope (Lecroy WaveRunner 6051) for various repetition rates, at the higher pump energy. An empirical function was fitted to the flashlamps emission, and this function was used as the pumping term \( I_p(t) \) to numerically solve the population rate equation for the Cr:LiSAF system:

\[
\frac{dN_2}{dt} = N_0 I_p(t) - \frac{N_2}{\tau} \quad (2)
\]

where \( N_0 \) and \( N_2 \) are the \( \text{Cr}^{3+} \) ground and excited state populations, respectively, and the spontaneous emission follows the excited state population \( N_2(t) \). The lifetime of the excited state, \( \tau \), was considered as an adjustable parameter and was tuned to obtain the best agreement between the acquired data for the spontaneous emission and the \( N_2(t) \) curve resulting from equation (2) numerical integration. This was done for 100 J pumping and repetition rates ranging from 2 Hz to 30 Hz. For all repetition rates, the best agreement between the experimental and numerical Cr:LiSAF spontaneous emission curves always occurs for \( \tau = 64 \mu s \). In figure 5, the measured flashlamps emission and rod spontaneous emission temporal profiles are presented together with the flashlamp
temporal fit and the emission numeric solution for 4 Hz and 30 Hz repetition rates. The fact that the same lifetime (64 µs) provided the best agreement for all repetition rates from 2 Hz to 30 Hz indicates that there is no quenching of the luminescence due to increased thermal load in the crystal as the repetition rate grows. The energy drop shown in figure 4 is probably due to changes in the flashlamps and in the power sources behavior and efficiency, as the repetition rate increases, what is hinted by the almost 5% increase in the flashlamps pulse duration observed at 30 Hz when comparing to 4 Hz (shown in figure 5).

Figure 5 - experimental flashlamps emission at 100 J (open squares) and Cr:LiSAF spontaneous emission (open circles), with the empirical function fitted to the flashlamps emission and the numerical solution of the Cr:LiSAF rate equation for τ=64 µs (solid lines). In the curves for a) 4 Hz and b) 30 Hz, the flashlamp pulse duration (FWHM) is indicated.

Conclusions

We developed a flashlamp pumped Cr:LiSAF resonator with reduced thermal load in the crystal rod, so the laser repetition rate could be increased. The final repetition rate is over reported values at which the rod is damaged. The laser performance was characterized providing fundamental parameters as resonator losses and threshold gain. Although the efficiency was reduced by the insertion of filters that prevented the pumping of the higher energies absorption bands, a threshold gain over 0.3 was measured and the laser could be operated at 30 Hz with an average power of 20 W. No noticeable decrease in the lifetime of the laser transition was observed in the range of repetition rates used, implying that our design could avoid significant laser rod temperature rise. This indicates that the laser can be operated at even higher repetition rates and higher powers.

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20) R. E. Samad and N. D. Vieira Jr, accepted for publication in Applied Optics