

Diode-pumped 100-fs passively mode-locked Cr:LiSAF laser with an antiresonant Fabry-Perot saturable absorber

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We demonstrate a self-starting passively mode-locked diode-pumped Cr:LiSAF laser, achieving pulses as short as 98 fs with an average power as high as 50 mW. In continuous-wave operation, we demonstrate 140 mW of output power with a tunability of 100 nm FWHM. These results were achieved by use of lower Cr³⁺ doping (1.5%), high-brightness diode lasers pumping from both sides of the crystal, and a low-loss antiresonant Fabry-Perot saturable absorber to start and sustain mode-locked operation.

Chromium-doped LiSrAlF₆ (Cr:LiSAF) is being widely investigated as a crystal for compact, tunable, low-cost mode-locked lasers with pulse widths below 100 fs (Refs. 1 and 2) because of its large linewidth (≈ 200 nm) and its absorption band near 670 nm, where diode laser pump sources are available. Recently, pulses as short as 220 fs were reported³ from such a system. However, obtaining short pulses with good average power is a challenge in a diode-pumped Cr:LiSAF because of its low small-signal gain compared with that of other materials in diode-pumped lasers such as Nd:YAG, Nd:YLF, or Nd:glass; the lower brightness of currently available laser diodes at 670 nm compared with that of laser diodes near 800 nm; and the quenching of its upper-state lifetime at temperatures that exceed approximately 50 °C.

The characteristics described above explain why the first mode-locked results used diffraction-limited pumps,^{4,5} resulting in pulses as short as 33 fs.⁶ The pump power required to demonstrate self-mode locking in these cases was comparable with powers available from diodes. However, the main constraint on longitudinal end pumping is mode matching, which means that the pump light must be focused to a size approximately equal to or less than the laser mode size in the crystal, over the pump absorption length. High-power diode lasers emit a beam with asymmetric, non-diffraction-limited properties. In the direction perpendicular to the junction, the beam is nearly diffraction limited, whereas in the other direction parallel to the junction, the beam is many times diffraction limited. In practice this means that the laser mode size inside the crystal is limited primarily by the pump beam quality in the direction parallel to the junction to achieve mode matching.

To obtain the highest small-signal gain, we wish to use the smallest laser mode size that we can mode match with our pump. By using a simple model,⁷ we can calculate the smallest spot size diameter d_{\min} to which a diode of a given stripe size l_x and divergence Θ_x can be mode matched over an absorption length $L \approx \alpha^{-1}$ of the crystal. We accomplish this by focusing the diode stripe into the middle of a cylinder

of length L , using geometrically imaging and then choosing the magnification factor of the imaging system to minimize the size of the beam at the entrance to the cylinder (end of the crystal). The result is

$$d_{\min} = \sqrt{L l_x \Theta_x}. \quad (1)$$

Focusing to a smaller spot will increase the divergence and overfill the cylinder at either end. A larger spot will have less divergence but will overfill the cylinder along the entire length. Although this model is rather simple for typical diode-pumped cases, it will give us important insights into the scaling described in the next few paragraphs.

We also can estimate the temperature rise in the center of the crystal that is due to the absorbed pump power. Using a simple model of homogenous heat flow from a cylinder, we assume that the pump power is uniformly deposited within a cylinder of radius r and length L ($\approx \alpha^{-1}$). Assuming that the edge of the crystal of radius R is held at a fixed temperature in a perfect heat sink, the temperature rise at the center of the pump is

$$\Delta T = \frac{Q_0}{4\pi k L} \left[1 + 2 \ln\left(\frac{R}{r}\right) \right], \quad (2)$$

where Q_0 is the deposited heat and k is the thermal conductivity. This temperature rise scales linearly with the absorbed pump power and inversely with the absorption length. Because of the logarithmic factor, changing the pump spot size of the crystal does not strongly affect the temperature rise. As the temperature approaches a critical value (the upper-state lifetime is reduced by one half at approximately 70 °C in Cr:LiSAF⁸), the small-signal gain significantly decreases. For a given pump power, therefore, there is a minimum absorption length (or maximum doping level) beyond which laser operation is no longer efficient, given a certain heat-sink temperature.

Given a pump diode with a large stripe size, Eq. (1) tells us that we can mode match by decreasing the absorption length, thereby allowing for tighter pump focusing and better mode matching. However, Eq. (2)

tells us that the decreased absorption length will increasingly limit the maximum pump power because of upper-state lifetime quenching. The other option to improve laser performance is to decrease either the diode stripe length l_x or its parallel divergence Θ_x . The justification for our approach is the use of shorter-stripe diodes, which permits longer absorption length (lower-doped crystals) and higher pump power. Cooling the crystal will also permit stronger pumping, but in our experiments we cool the laser crystal only to temperatures readily achievable with thermoelectric coolers and avoid near-freezing or sub-freezing temperatures, which would require isolating the crystal from humid air.

Figure 1 shows the setup of the laser cavity for both cw and mode-locked operation. In all experiments, the crystal heat-sink temperature was held at $\approx 10^\circ\text{C}$ unless otherwise noted. Two diodes, with 400 mW of output power at 670 nm and emitting from 100- μm stripes with 6° divergence parallel to the junction (Applied Optonics AOC-670-400), pump a 5-mm-long Brewster/Brewster 1.5% Cr:LiSAF crystal from both sides. The pump beam is collected in its fast diverging direction by a 200- μm -diameter round cylindrical fiber lens with a refractive index of 1.8. The astigmatism introduced by the fiber lens is negligible, allowing the first round achromatic lens ($f = 200$ mm) to collimate both directions simultaneously. Then the beam is refocused through a cavity mirror by the second lens ($f = 120$ mm). Using a beam scan with a moving slit aperture, we measured the minimum spot size at the crystal position to be 80 μm in diameter (10% clip level), with a far-field full-angle divergence of 8° (≈ 13 times diffraction limited) in the direction parallel to the diode junction, and 60 μm in the other direction, with a divergence of 2° . This provides mode matching to the 100 $\mu\text{m} \times 140 \mu\text{m}$ diameter of the laser mode over the ≈ 1 -mm absorption length of the crystal, approximately following Eq. (1).

We investigated the effect of upper-state lifetime quenching on laser efficiency by tuning the crystal heat sink temperature up to 50°C , with two different Cr $^{3+}$ doping levels and three output couplers (Fig. 2). With 3% Cr:LiSAF (absorption length $L \approx 0.5$ mm), the output power decreased at lower temperatures than for the lower 1.5% doping ($L \approx 1$ mm). For an ideal four-level laser, increasing the laser's total losses (i.e., increasing output coupling) normally causes the laser threshold to increase proportionally. However, in Cr:LiSAF this extra pump power deposits more heat, increasing the crystal temperature and decreasing the upper-state lifetime and the small-signal gain. Therefore reaching threshold requires more pump power, resulting in reduced laser output power. This shows the significance of keeping the intracavity losses as low as possible to prevent thermal upper-state lifetime quenching from dramatically reducing the laser's efficiency.

Using the 1.5% doped crystal and both diodes, we obtained 140 mW of output power with a 2% output coupler in the cw cavity (580 mW of absorbed pump power and a laser threshold of 160 mW). After inserting a birefringent plate, we obtained approximately 100 mW of average power, tunable over

a range of 100 nm FWHM [Fig. 3(a)], limited by our cavity mirrors. The linewidth was measured to be less than 0.1 nm, the resolution limit of our optical spectrum analyzer.

To mode lock the laser, we chose to use an antiresonant Fabry-Perot saturable absorber (A-FPSA), which has successfully demonstrated self-starting mode locking in several Nd-doped lasers.⁹⁻¹¹ For this experiment, we fabricated a structure for ≈ 830 nm as shown in the inset of Fig. 1. The saturable absorber consists of a low-temperature-grown ($T = 350^\circ\text{C}$) multiple-quantum well layer with a peak in the excitonic absorption at 830 nm, embedded between the two mirrors. The lower mirror is molecular-beam-epitaxy grown, and the top mirror is evaporated. The A-FPSA, operating at antiresonance at 830 nm, has a free spectral range of more than 100 nm. However, the overall range of this specific A-FPSA is limited to ~ 50 nm by the bandwidth of the bottom mirror. We measured a bitemporal reflectivity response with a slow recovery time of 16 ps owing to recombination and a fast recovery time of 150–200 fs owing to intraband thermalization of the carriers.¹² The slow recovery time provides sufficient modulation for the longer pulses in the start-up phase, and the faster recovery time contributes to the femtosecond pulse formation. We consider the A-FPSA instead of Kerr-lens mode locking to be the dominating effect, because the laser was operated in the middle of the cavity stability regime, not close to the cavity stability limit as is usually the case in achieving significant Kerr-lens mode locking.

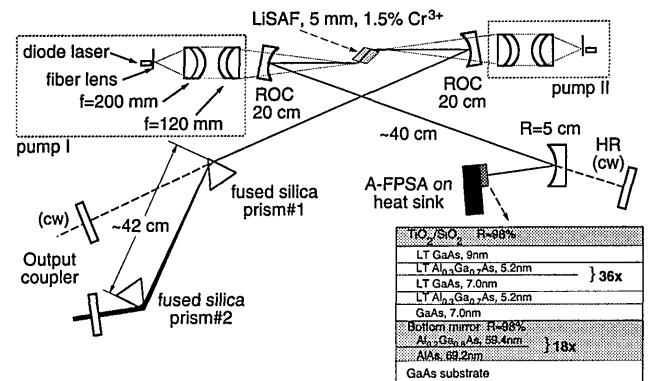


Fig. 1. Schematic of the laser cavity. HR, high reflector; ROC, radius of curvature.

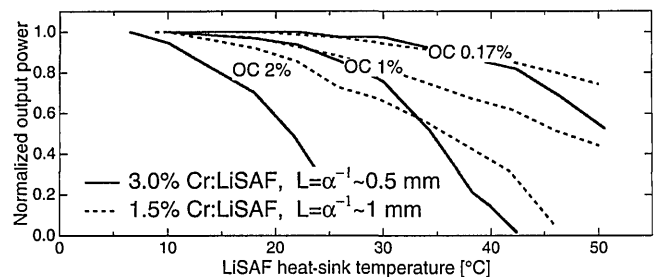


Fig. 2. Normalized output power versus crystal heat-sink temperature for two different crystal doping levels (1.5% and 3%) and three different output couplers (OC's) (0.17%, 1%, and 2%). The absorbed pump power was kept constant at 300 mW.

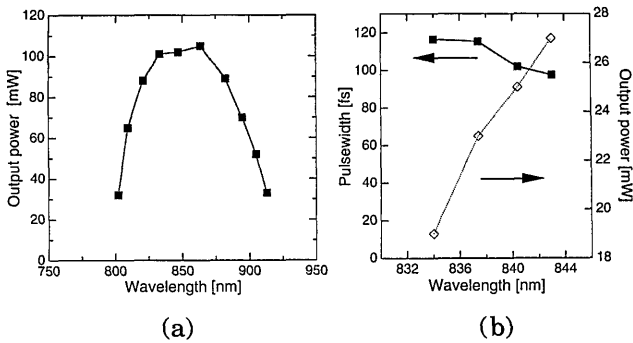


Fig. 3. (a) Cw tunability over 100 nm FWHM with a birefringent plate, (b) mode-locked tunability of approximately 10 nm. The wavelength was tuned with a knife edge inserted into the laser beam between the two prisms.

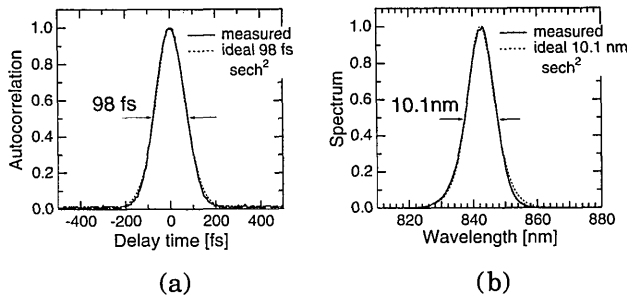


Fig. 4. (a) Mode-locked pulse width with a noncollinear autocorrelation, (b) the corresponding optical spectrum.

In addition, the intensity-dependent nonlinearity is much smaller, because of the larger laser mode size inside the laser crystal required by diode-pumping, than in typical Kerr-lens mode-locking lasers, such as Ti:sapphire lasers.

To achieve mode-locked operation, we reconfigured the cavity as shown in Fig. 1 by inserting dispersion compensation prisms in one arm, replacing one end mirror with a curved mirror that focuses the laser beam onto the A-FPSA with a 15- μm radius, and reducing the output coupler to 1%. Self-starting mode locking was obtained with sub-100-fs pulses of 27-mW average output power (Fig. 4) at a repetition rate of 120 MHz.¹³ The optical spectrum was 10 nm wide, giving a time-bandwidth product of 0.42. We measured mode-locked wavelength tunability over a range of 10 nm by inserting a knife edge into the laser beam between the two prisms [Fig. 3(b)]. The system exhibits good long-term stability, with the output power and pulse width remaining constant for hours.

Using an A-FPSA with reduced insertion losses (1% instead of 2%), we increased the output coupling to 2% while keeping the total losses and therefore the intracavity power the same. This resulted in approximately twice as much average output power than before, as we would expect, and again we measured near-transform-limited 100-fs pulses with an average output power of 50 mW.

The use of the A-FPSA structure, compared with the use of an antireflection-coated multiple-quantum-

well saturable absorber,³ was critical for reducing the insertion loss of the device because, as was seen in the cw measurements, we pay an extra penalty in terms of laser efficiency for all added loss to the laser because of the thermal quenching of the upper-state lifetime. One limitation of our current devices is tunability. However, tunability of greater than 100 nm has been demonstrated¹⁴ with similar multiple-quantum-well saturable absorbers in a coupled-cavity mode-locked Ti:sapphire laser. With proper design of the saturable absorber and the lower molecular-beam-epitaxy-grown mirror, we expect that comparable tunability also should be possible. Finally, although a Kerr-lens mode-locked diode-pumped Cr:LiSAF laser should be possible, features of the A-FPSA are its ability to provide enough saturation for self-starting of the laser even at the lower laser powers available with diode-pumping and to allow the cavity to be designed in the center of its stability range, where we can achieve the most robust performance.

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