1.1-W cw Cr:LiSAF laser pumped by a 1-cm diode array

D. Kopf and U. Keller

Ultrafast Laser Physics, Institute of Quantum Electronics, Swiss Federal Institute of Technology, ETH Hönggerberg-HPT, CH-8093 Zürich, Switzerland

M. A. Emanuel, R. J. Beach, and J. A. Skidmore

Lawrence Livermore National Laboratory, P.O. Box 808, L-250, Livermore, California 94550

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We demonstrate 1.1-W cw output power from a diode-laser array-pumped Cr:LiSAF laser based on a concept that allows for pumping low-gain solid-state lasers at reduced temperature rise. We discuss scaling to higher powers as a function of diode power and define a figure of merit for evaluating given diode lasers as pump sources for low-gain solid-state lasers. © 1997 Optical Society of America

Diode-pumped solid-state lasers are commonly used in a variety of applications. High-power diode-laser arrays were shown to pump efficiently a number of laser media, such as Nd:YAG, Yb:YAG, and Nd:YVO_4, [1] that have relatively high gain. For the case of Cr:LiSAF, however, increased output power was typically limited by highly non-diffraction-limited laser-diode pump beams and by upper-state lifetime quenching.[2] In this Letter we discuss a concept that permits efficient pumping of low-gain laser media with a high power diode-laser array at reduced heating at the pump spot. Based on these considerations, we experimentally demonstrate a cw output power of 1.1 W from a diode-pumped Cr:LiSAF laser[3] in which the reduced temperature rise helps to avoid upper-state lifetime quenching.

Cr:LiSAF (Ref. 4) is an interesting gain medium for a variety of laser applications. It can be pumped near 670–690 nm, and its broad emission bandwidth supports both wavelength tunability and femtosecond pulse generation. Therefore diode-pumped Cr:LiSAF lasers are attractive as potentially inexpensive replacements for Ti:sapphire lasers. However, standard diode pumping of Cr:LiSAF has typically yielded output powers of less than ~230 mW cw[5,6] and less than ~120 mW mode locked.[7] These experiments have emphasized the use of high-brightness diode-laser pumps. For example, one experiment used two 0.4–0.5-W diodes that emitted a 12-times diffraction-limited beam that is absorbed over a relatively short (0.5–1-mm) absorption length.[5] The use of high-brightness diode-laser pumps facilitates mode matching of the pump beam to the laser mode over the absorption length. However, the increased temperature rise at the pump spot that is due to the desired short absorption length, in combination with upper-state lifetime quenching of Cr:LiSAF, has limited further scaling toward higher output powers.[2,8]

Diode-laser arrays typically emit a beam that is diffraction limited in the direction perpendicular to the diode junction (y) and non-diffraction limited in the plane of the junction (x). For example, the beam quality factors[9] of a 1-cm-wide diode array are typically ${M_x}^2 \approx 1$ and ${M_y}^2 \geq 1000$, respectively. To achieve the highest possible pumping efficiency or, equivalently, small-signal gain, we have to focus the pump beam to a pump spot area that is as small as possible, while maintaining a good overlap of the pump beam with the laser mode over the absorption length. Therefore the confocal parameters of the pump beam in the two transverse directions, b_x and b_y, should be approximately equal to the absorption length L (Refs. 10 and 11):

$$b_x \approx b_y \approx L\,. \qquad (1)$$

This leads to an optimized mode matching (OMM) condition, assuming that we can shape both the pump beam and the laser mode independently to any desired waist in both transverse directions, x and y. The pump beam waists in the laser medium, $w_{0,x}$ and $w_{0,y}$, can then be determined from[11]

$$L \approx b_{x(y)} \approx 2\pi w_{0,x(y)}^2/[\lambda_n {M_{x(y)}}^2]\,. \qquad (2)$$

This results in an asymmetric pump beam and laser mode for ${M_x}^2 \gg {M_y}^2$. Earlier experiments achieved an asymmetric lasing mode with either an anamorphic prism beam expander inside the cavity[12] or a cylindrical cavity mirror.[11,13] Following relation (2) and using $g_0 \sim (w_{0,x}w_{0,y})^{-1}$, we see that the OMM leads to a small-signal gain g_0 and a corresponding figure of merit (FOM) for a given absorption length as follows:

$$g_0 \propto \frac{P}{L\sqrt{{M_x}^2{M_y}^2}}\,, \qquad \mathrm{FOM} = \frac{P}{\sqrt{{M_x}^2{M_y}^2}}\,\cdot \qquad (3)$$

Here P is the pump power, L is the absorption length, and $M_{x(y)}^2$ are the pump beam quality factors. As we scale toward higher pump powers P, we can assume that $P \propto {M_x}^2$ and ${M_y}^2 \approx 1$. This is justified because diode-laser arrays typically scale their output power proportional to the array width at approximately fixed divergence.[14] Therefore OMM leads to an increasing FOM with increasing diode power, despite the decreased diode beam quality (for fixed L):

$$\mathrm{FOM} \propto \sqrt{{M_x}^2} \propto \sqrt{P}\,. \qquad (4)$$

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Relations (3) and (4) allow us to determine whether a laser diode with parameters P, ${M_x}^2$, and ${M_y}^2$ is suitable for pumping a given solid-state laser material. For this purpose we compare such a laser with a diffraction-limited source with ${M_x}^2 = {M_y}^2 = 1$. For example, a diode array width $W_x = 1$ cm, 10-W diode-laser array emitting at 690 nm with a divergence of $\theta = \pm 4.5°$ (in x) has an $M_x^2 = \pi(W/2)\ \theta/\lambda = 1800$ and results in $\text{FOM} = 10\ \text{W}/\sqrt{1800} = 0.235\ \text{W}$. This is equivalent to, or has approximately the same small-signal gain as, a diffraction-limited pump with $\text{FOM} = 0.225\ \text{W}$ (TEM_{00}), provided that OMM is achieved. Knowing that Cr:LiSAF can be pumped by a diffraction-limited source of 225 mW, we conclude that pumping with a 10-W diode array should be possible, assuming that the elevated temperature rise does not prevent efficient laser operation (see below).

Based on these considerations, we have constructed a Cr:LiSAF laser pumped by a diode-laser array emitting at 690 nm from a 1-cm-wide facet at a divergence of ±4.5°.[14] A cyclindrical microlens mounted close to the emitting facet collected the diode light in the strongly divergent direction (y). The diode was operated up to an output power of 12 W. The pump diode beam was imaged into the laser crystal to a spot size of <2 mm × 150 μm (diameter) over the absorption length of 4 mm, after ≈25% of the diode pump beam was apertured for improved focusing. At the position of the laser medium, we measured a pump beam quality of ${M_x}^2 <\approx 1000$ and ${M_y}^2 \approx 4$, using a moving-slit beam scan. The pump focusing optics (Fig. 1) consists of two cylindrical lenses ($f_y = 60$ mm and $f_x = 300$ mm) that collimate the diode beam in both x and y, followed by a spherical achromat ($f_{xy} = 80$ mm) and a meniscus lens (Melles-Griot 01LMP003).

To remove the generated heat efficiently and thus avoid upper-state lifetime quenching,[2] we chose a long absorption length (4 mm) and a low crystal height (1 mm). The heat is generated over the absorption length in a pump volume of approximately 2 mm × 4 mm × 150 μm and then removed with a mainly one-dimensional heat flow [Fig. 2(a)] across the 1-mm crystal height. This arrangement, consisting of a strongly asymmetric beam in a vertically thin gain medium, has the following advantages.

First, the temperature rise at the pump spot is kept low enough to avoid upper-state lifetime quenching in Cr:LiSAF. To verify this, we performed numerical heat-flow simulations,[15] assuming homogeneous heat deposition over the absorption length and two-dimensional heat flow in the x–y plane. The resulting temperature profile along the x direction [Fig. 2(b)] shows a maximum temperature rise of 35 °C at a total deposited heat of 3 W, which corresponds approximately to the experimental condition. Therefore we can keep the crystal heat-sink temperature at slightly below room temperature (10 °C) and avoid subfreezing temperatures or condensation from humid air.

Second, we can scale up the pump power at fixed pump intensity, and thus fixed small-signal gain, without significantly increasing the temperature rise, simply by expanding the spot dimension in the x direction. The maximum temperature as a function of increasing spot diameter in x ($\approx 2w_{0,x}$) strongly saturates owing to the one-dimensional heat flow, as numerical simulations show [Fig. 2(c)]. This arrangement, therefore, scales to higher pump powers without significantly increasing the temperature, as would be the case for a standard pump arrangement with round beams.[5]

Third, the asymmetric pump beam and lasing mode fit into the flat, slablike medium without any significant aperturing losses because the crystal dimension is generally >3–4 times the mode diameter in each transverse direction. In comparison, a standard setup with a round lasing mode and equivalent temperature rise (35 °C) would have to use a laser medium with a diameter for which the aperture losses can no longer be neglected. As an example, we have calculated the maximum temperature rise of a 0.7-mm-diameter Cr:LiSAF crystal to be 37 °C, assuming the same absorption length (4 mm) and equivalent deposited heat (3 W) as we used in our experiment, in a circular spot of radius 223 μm. One could accomplish this with a 1-cm diode array, using the beam-shaping arrangement described in Ref. 16. This would, in principle, lead to equivalent small-signal gain because the same pump intensity as that in our setup is used.

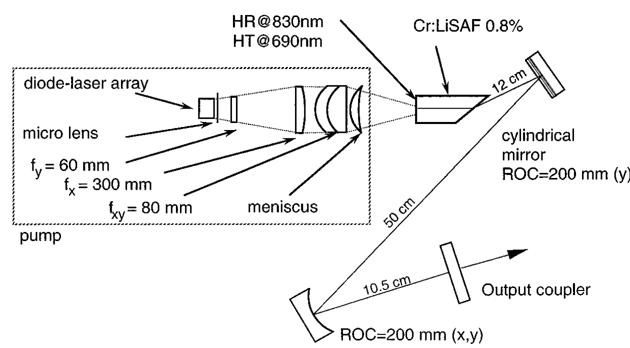

Fig. 1. Laser setup of a diode-pumped Cr:LiSAF laser with a 1-cm-wide diode-array. HR, high reflector; HT, high transmission; ROC, radius of curvature.

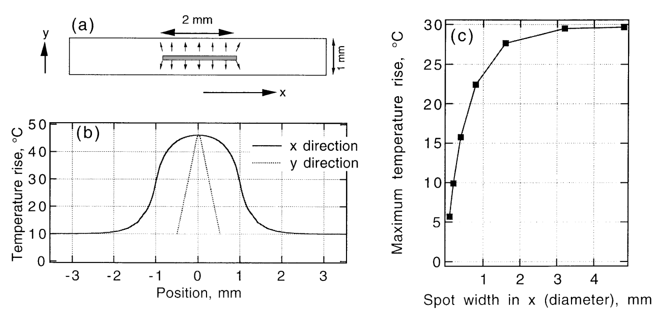

Fig. 2. (a) Cross-sectional view across the laser crystal with a one-dimensional heat flow (arrows) from a 2 mm × 150 μm pump shot (shaded area). (b) Temperature profile through the pump spot in both transverse directions x and y, as obtained from (two-dimensional) numerical heat-flow simulations. (c) Maximum temperature rise (calculated) as the pump spot diameter in the x direction is expanded at constant pump intensity at the pump spot. For spot widths greater than 2 mm, the predominantly one-dimensional heat flow causes no significant increase in temperature rise despite the increased total amount of deposited heat.

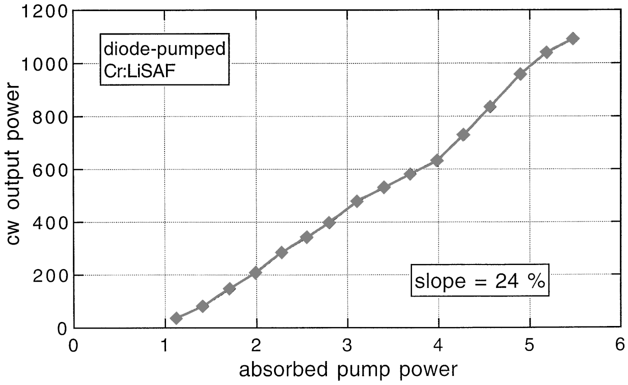

Fig. 3. Measured cw output power at 863 nm as a function of absorbed pump power from the diode-laser array pump source.

However, at this laser mode size and crystal size, the calculated aperture losses would be 1.1%, which is undesirable for low-gain lasers.

The cavity layout in our Cr:LiSAF experiment (Fig. 1) uses a cylindrical resonator mirror (vertical radius of curvature 200 mm) that focuses the lasing mode to a strongly asymmetric spot at the gain end, matched to the pump beam. Based on *ABCD* matrix calculations, we calculated a spot of 1500 μm $\times$ 120 μm diameter in the crystal. After the cylindrical mirror, the laser mode is approximately round, thus providing a round circular output beam.

The output power at a wavelength of 863 nm as a function of absorbed pump power is shown in Fig. 3 and has a slope of 24%. The output coupling was 1%. At a maximum absorbed pump power of 5.5 W, we obtained a cw output power of 1.1 W without significant saturation, as expected from the temperature profile calculations. We measured the output beam quality with a moving-slit beam scan at two positions and determined the beam to be near diffraction limited with an $M_x^2 \approx M_y^2 \approx 1.4$. We attribute this less-than-perfect beam quality to the pump beam, which tends to have higher intensities at the edges of the diode-laser array and, therefore, causes some mode perturbation.

In conclusion, we have described and demonstrated a concept that allows Cr:LiSAF to be pumped with a diode-laser array at reduced temperature rise to avoid upper-state lifetime quenching, and we demonstrate 1.1-W cw output power. We discuss the scaling of this concept to higher pump powers and define a figure of merit with respect to the achievable small-signal gain for a given diode-laser array. We anticipate that this concept may be applicable to other solid-state laser systems with low gain and critical thermal properties.

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