400-mW continuous-wave diode-pumped Cr:LiSAF laser based on a power-scalable concept

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A high-power diode-pumped Cr-doped $LiSrAlF_6$ (Cr:LiSAF) laser with an output power of 400 mW cw is experimentally demonstrated. The power-scalable concept involving at least one cylindrical cavity mirror is discussed with respect to mode-matching requirements and thermal limitations. Simple arguments indicate that our approach allows one to scale the output power of a Cr:LiSAF laser to the multiwatt level. This is further supported by a comparison with other high-power concepts for diode-pumped solid-state lasers.

Diode-pumped Cr-doped $LiSrAlF_6$ (Cr:LiSAF) lasers attract interest as an inexpensive replacement for Ar-ion-pumped cw or ultrafast Ti:sapphire lasers. However, so far only ≈200 mW of cw power has been obtained with high-brightness pump laser diodes,[1,2] limited by the non-diffraction-limited pump beam, the poor thermal conductivity, and the upper-state lifetime quenching of Cr:LiSAF. In this Letter we present a 400-mW cw diode-pumped Cr:LiSAF laser that uses an alternative mode-matching scheme with optimized mode matching of the cavity and pump beam in both directions, i.e., in the tangential and the sagittal planes. A cylindrical mirror was used to produce an elliptical lasing mode matched to the diode pump beam. The concept of an asymmetric cavity mode in the gain medium was first demonstrated in a high-power Nd:YAG laser[3] by the use of intracavity anamorphic prism beam expanders. In addition, cavities with cylindrical mirrors have been theoretically investigated[4] and recently have been suggested for diode pumping.[5] The cylindrical cavity mirror approach demonstrated in this Letter permits the use of higher-power diode pump lasers despite their lower beam quality and has the advantage of smaller intracavity losses and less intracavity group-velocity dispersion, both important for cw as well as short-pulsed Cr:LiSAF lasers.

Throughout this Letter we assume that optimum mode matching in both transverse directions simultaneously is governed by the requirement[2,6]

$$b_x = b_y = L\,, \tag{1}$$

where b_x and b_y are the confocal parameters of the pump beam inside the gain medium in the tangential and the sagittal planes, respectively, and L is the absorption length. The beam quality of the pump beam in the tangential and the sagittal planes is quantified by the times-diffraction-limited factors M_x^2 and M_y^2. The confocal parameter is given by $b_{x(y)} = 2\pi\omega_{0,x(y)}^2/[\lambda_n M_{x(y)}^2]$, where $\omega_{0,x(y)}$ is the pump beam waist and λ_n is the wavelength in the medium.[7] Therefore Eq. (1) is fulfilled when

$$\omega_{0,x}^2 M_y^2 = \omega_{0,y}^2 M_x^2 = \frac{L\lambda_n}{2\pi} M_x^2 M_y^2\,. \tag{2}$$

The laser mode waist inside the gain medium is approximately equal to the pump beam waist for optimum mode matching.[8] Then the laser mode area is

$$A_{xy} = \pi\omega_{0x}\omega_{0y} = \pi\omega_{0x}^2\sqrt{M_y^2/M_x^2} = \frac{L\lambda_n}{2\pi}\sqrt{M_x^2 M_y^2}\,. \tag{3}$$

The desired cavity mode defined in Eq. (2) has an ellipticity factor of $R = \sqrt{M_x^2/M_y^2}$. The laser mode area and therefore the laser pump threshold are reduced by R compared with those for the standard approach with a round cavity mode, in which perfect mode matching is accomplished only in the tangential direction (if $M_x^2 > M_y^2$). Note that if a Bewster-cut medium is used, R can be multiplied by the refractive index n of the gain medium, as the cavity mode already has an aspect ratio of n.

The experimental setup is shown in Fig. 1. The cavity consists of a flat/Brewster gain-at-the-end Cr:LiSAF crystal (Lightning Optical Corporation; 3% Cr doping, 4 mm × 4 mm cross section, 5-mm length); a cylindrical cavity mirror [radius of curvature (ROC) in the sagittal plane ROC_y = 50 mm]; a spherical mirror (ROC_{xy} = 150 mm); and a flat output coupler. The gain medium is pumped from both sides with temperature-stabilized high-power AlGaInP/GaInP diode laser arrays,[9] each emitting 1.2-W cw power at a wavelength of 690 nm. The emitting area of the laser array of 580 μm × 1.2 μm FWHM is formed by 36 lasers on 16-μm centers with 8-μm-wide ridge waveguides. These diodes exhibit an $M_x^2 = 120$ ($M_y^2 \approx 1$) times-diffraction-limited beam

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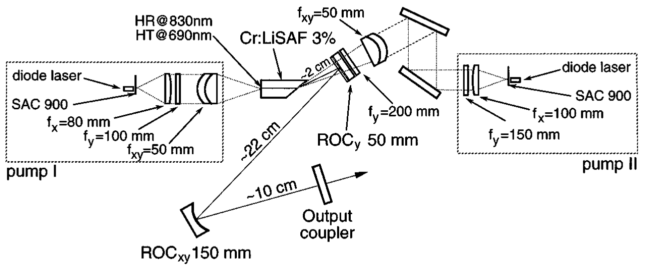

Fig. 1. Experimental setup using a flat/Brewster-cut Cr:LiSAF crystal, a cylindrical cavity mirror, a spherical mirror, and a flat output coupler. x denotes the tangential plane, y the sagittal direction. HR, highly reflecting; HT, highly transmitting; SAC 900, single-axis-collimator cylindrical microlens (Blue Sky Research).

in the tangential (sagittal) plane. For mode matching, the pump beam was focused to a waist of approximately 120 μm $\times$ 30 μm radius, close to the theoretically calculated waist of 120 μm $\times$ 15 μm [Eq. (2)]. The cavity layout was chosen for a beam waist of 200 μm $\times$ 30 μm in the gain medium, closely matched to the pump beam. The rotational adjustment of the cylindrical cavity mirror around the axis perpendicular to the mirror was found to be a critical parameter. At 1.6-W absorbed pump power we generated a maximum cw output power of 400 mW (Fig. 2), measured with a calibrated powermeter (Coherent Field Master with LM-150FS head). The wavelength of the laser output could be tuned over 80 nm FWHM by a two-plate birefringent tuning element from a commercial Coherent cw Ti:sapphire laser (inset in Fig. 2). With this cavity layout, the output beam after the output coupler was a round TEM_{00} mode with no visible ellipticity.

In principle, we can simply scale this concept to higher-power levels by tangentially extending the pumped volume (and the cavity mode correspondingly) while maintaining the same pump intensity [Fig. 3(b)] and therefore the small-signal gain. Higher-power pump diode designs with wider emitting areas naturally fit this scaling. According to Eq. (2), for an absorption length twice as long, mode matching is still achieved if the pump diode laser output power scales linearly with M_x^2 [i.e., for twice the diode power at twice the M_x^2, Eq. (2) gives us an L twice as long]. Both simple analytical estimations and numerical heat-flow simulations[10] show that even in the theoretical limit of an infinitely wide pump/cavity mode the maximum temperature stays within a factor of 5 compared with that in our experiment. This means that scalability is feasible, because we can compensate for this increase in heat deposition by choosing an absorption length twice as long and reducing the crystal height to a two-times-smaller value. This reduces the temperature rise by the same factor, assuming that we are close enough to the limit of an infinitely wide pump/cavity mode where the heat flow is one-dimensional rather than radial (Fig. 3). This keeps the maximum temperature in the gain medium at approximately the same level as in our experiment and therefore prevents upper-state lifetime quenching of Cr:LiSAF.

In addition, we expect no thermal lensing limitation because the sagittal thermal lens is uncritical, as discussed below, and the tangential thermal lens is negligible. The transverse temperature profile in the tangential plane is theoretically constant, as no heat flows in that direction [Fig. 3(b)]. In our experiment, however, this was found to be the dominant thermal lens because the heat flow is not a one-dimensional problem [Fig. 3(a)].

We estimated the thermal temperature profile in the gain medium with a numerical two-dimensional heat-flow simulation.[10] The resulting transversal temperature profile curvature in the tangential plane turned out to be five times smaller than in the sagittal direction, with $\partial^2 T/\partial x^2 = 2.7 \times 10^9$ K/m^2 and $\partial^2 T/\partial y^2 = 1.3 \times 10^{10}$ K/m^2, respectively, for 1 W of absorbed heat in the crystal. This corresponds approximately to the ellipticity factor of our pump beam. We modeled the thermally induced refractive-index profile as a Gaussian duct over the absorption length and the thermal elongation at the end surfaces as curved surfaces,[11] using the material constants of Cr:LiSAF from Ref. 12. As a result, for our cavity setup the sagittal thermal lens turned out to be uncritical, which means that even several times higher pump levels would not make the cavity unstable. In our particular cavity layout, however, cavity stability was found to be approximately 10 times more sensitive to the tangential thermal lens. This drives the laser close to the stability limit when it is operated at maximum power. The small anisotropy of the thermal properties of LiSAF is not dominant. This explains the saturation of the output power, as shown in Fig. 2. Upper-state lifetime quenching is not responsible because a similar roll-off would have to occur for the first diode as well (see section I in Fig. 2) because the laser crystal (5-mm lngth) was pumped from both sides with an absorption length of 1 mm. We can assume that

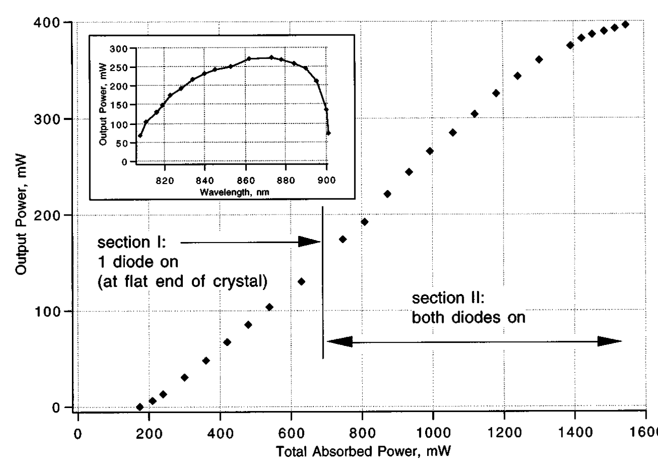

Fig. 2. Measured output power versus absorbed pump power with a 1% output coupler and a Cr:LiSAF heat-sink temperature of 10 °C. The laser threshold is at 160-mW absorbed pump power, the slope efficiency is approximately 30%, and the overall electrical-to-optical efficiency is 0.4 W/15 W = 2.7%. We could tune the laser wavelength over a range of 80 nm FWHM by using a two-plate birefringent tuning element (inset).

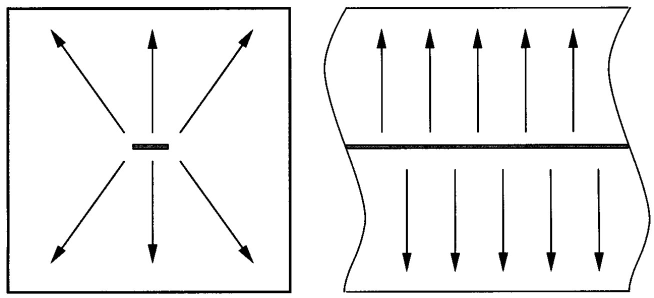

Fig. 3. Diagrams of the pump and mode areas inside the gain medium; the heat-sink contacts are on the top and at the bottom. (a) Present situation, (b) scaling of the pump beam tangentially, maintaining the same pump intensity. Heat flux is only in the vertical (sagittal) direction, which can be treated in a one-dimensional model.

thermally induced birefringence is negligible because the Brewster reflection is small (<10 mW).

In previous research the laser-diode pump beam was made symmetric by a beam-shaping technique.[13] Using the laser-diode pump beam ($M_x^2 \gg 1$, $M_y^2 \approx 1$) without beam shaping gives an optimum cavity mode area of $A_x \approx L\lambda_n M_x^2/(2\pi)$ in the gain medium, assuming a standard symmetric-mode cavity with optimized mode matching only in the tangential plane. After pump beam reshaping, the mode area turns out to be $A_x \approx L\lambda_n\sqrt{M_x^2}/(2\pi)$ for optimum mode matching. This produces the same pump threshold reduction factor $R = \sqrt{M_x^2}$ as in our elliptic-mode approach. However, this approach provides limited scalability for Cr:LiSAF systems, as the heat flow remains radial and therefore the pump spot gets hotter with increased pump power.

In addition, recently the thin-disk laser was demonstrated as a power-scalable concept for diode pumping[14] with a thin disk of Yb:YAG as the gain medium. However, Cr:LiSAF has a 4-times-lower heat conductivity and an 8-times-higher saturation intensity, which requires an 8-times-higher pump intensity for an equivalent small-signal gain. Therefore Cr:LiSAF would exhibit at least a 32-times-higher (i.e., 4×8) temperature rise in an equivalent thin disk arrangement. As Yb:YAG already has a temperature rise of several tens of degrees celsius through the disk,[14] the temperature rise in a Cr:LiSAF thin disk laser can be estimated to be far above 100 °C even after further optimization such as the use of a much thinner disk. This is well above the critical temperature of ≈70 °C for upper-state lifetime quenching in Cr:LiSAF.[15] In addition, Cr:LiSAF has stronger excited-state absorption, which will further decrease performance at higher pump densities. Therefore the thin-disk laser concept is not very promising as a power-scalable concept for diode-pumped Cr:LiSAF lasers.

In conclusion, a high-power diode-pumped Cr:LiSAF laser with an output power of 400 mW cw has been demonstrated through optimized mode matching of the pump beam to the cavity mode. We have given simple considerations concerning mode matching, thermal limitations, and scalability. The concept was compared with other high-power concepts for diode-pumped lasers and found to be the most promising method for power scaling of diode-pumped Cr:LiSAF lasers.

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