

# Diode-pumped, single-frequency Cr:LiSrAlF<sub>6</sub> ring laser

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We report the development of a tunable, diode-pumped Cr:LiSrAlF<sub>6</sub> ring laser that emits as much as 43 mW of power in a single longitudinal mode at 849 nm. By tuning the output with a birefringent filter, we achieved single-frequency operation from 810 to 860 nm. The short-term (10-s) frequency stability was better than 15 MHz. © 1995 Optical Society of America

The Ti:sapphire laser has become an established source for cw, watt-level, single-frequency power from 680 to 1050 nm, but the commonly used Ar-ion laser pump source is a disadvantage for many applications. Tunable, external-cavity, single-frequency diode lasers are available for portions of this wavelength region, but a given diode laser can cover a range of only 15–25 nm. Cr:LiSrAlF<sub>6</sub> (Cr:LiSAF) is a possible alternative to Ti:sapphire for wavelengths beyond 780 nm, and the broad 600–700-nm absorption band permits pumping by InGaAlP diode lasers emitting near 670 nm. A single-frequency, coupled-cavity Cr:LiSAF laser emitting 5 mW of power at 870 nm was first demonstrated by Zhang *et al.*<sup>1</sup> Sutherland *et al.* reported the first diode-pumped, single-frequency Cr:LiSAF composite microlaser, which produced 1 mW of output power.<sup>2</sup> By modifying the microlaser cavity configuration, they achieved close to 10 mW of output power, but multifrequency operation was frequently observed. Another method of achieving single-frequency operation, which utilized a coupled cavity/grating resonator, was demonstrated by Vilain *et al.*<sup>3</sup> They produced 5 mW of single-frequency output power when the laser was pumped 30% over threshold. At higher pump powers the output was multifrequency, which, according to the authors, was probably due to spatial hole burning. Knappe *et al.* utilized an 850-nm, single-stripe diode laser to injection seed a Cr:LiSAF ring laser and achieved 20 mW of single-frequency output over a wavelength range limited by the diode-laser tuning.<sup>4</sup>

We report what is to our knowledge the first demonstration of a diode-pumped, broadly tunable, single-frequency, unidirectional ring Cr:LiSAF laser. To achieve stable, continuously tunable, single-frequency operation of Cr:LiSAF, we have chosen to employ an optical design similar to that used in commercial single-frequency ring Ti:sapphire lasers. All other parameters being equal, the peak cw gain of Cr:LiSAF should be approximately 2.6 times higher than for Ti:sapphire, given the ratio of the products of the peak effective gain cross sections ( $\sigma_{\text{eff}}$ ) and lifetimes ( $\tau$ ), where we assume  $\sigma_{\text{eff}}$  values of  $2.5 \times 10^{-19}$  and  $0.32 \times 10^{-19}$  cm<sup>2</sup> for Ti:sapphire<sup>5</sup> and Cr:LiSAF,<sup>6</sup> respectively, and  $\tau$  values of 3.2 and 67  $\mu$ s for Ti:sapphire<sup>7</sup> and Cr:LiSAF,<sup>8</sup> respectively. With conventional multimode diode pump sources the pump intensity available in the crystal is well below that from a TEM<sub>00</sub>-mode ion-laser pump, and thus even

with the  $\sigma_{\text{eff}}\tau$  product advantage over Ti:sapphire, operation of the diode-pumped tunable ring Cr:LiSAF laser is a challenge, requiring high-brightness diode lasers, proper pump-focusing optics, and low-loss intracavity optics. Since the lifetime of the upper laser level in Cr:LiSAF decreases with temperature and the temperature rise in the crystal is inversely proportional to the absorption length, we used a lightly doped crystal to minimize thermal loading and allow operation at high pump powers.<sup>9</sup> This places an even higher premium on high pump brightness, since the relatively small absorption coefficients of lightly doped materials require the use of long crystals for adequate pump absorption to be achieved, and the lowest threshold and the best slope efficiency occur when pump intensity is maintained over the entire length of the crystal.

Figure 1 shows the Cr:LiSAF ring laser layout. The four-mirror, figure-eight cavity contains a 2 mm (height)  $\times$  3 mm (width)  $\times$  5 mm (length) Brewster-cut Cr:LiSAF crystal, a two-plate birefringent filter (0.63:1.26 mm) for coarse tuning, a 1-mm-thick fused-silica étalon for fine tuning, and a Tb<sub>3</sub>Ga<sub>5</sub>O<sub>12</sub> (TGG) optical diode to ensure unidirectional operation. One could also operate the laser in a standing-wave configuration by adjusting the two flat mirrors (Fig. 1) for retroreflection. The two curved mirrors and the flat fold mirror were coated for high reflection between 780 and 900 nm and, for the two curved mirrors, 90% transmission at 670 nm; the reflectivity of the flat output coupler was between 99.0% and 99.5% from 800 to 880 nm. The Cr:LiSAF crystal, which had an absorption coefficient of 4.3 cm<sup>-1</sup> at 670 nm, was mounted on an uncooled copper block. We used two 0.5-W, 670-nm, 100- $\mu$ m-aperture InGaAlP diode lasers (Uniphase Model HP-067-0500-TM), one for each end

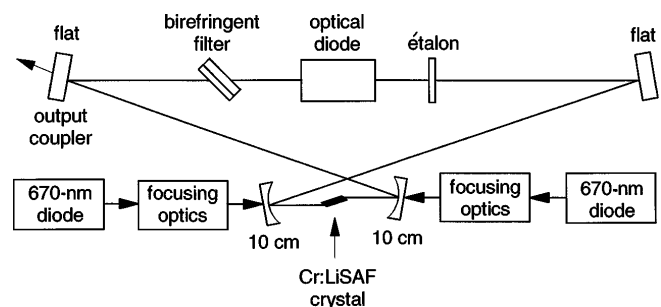


Fig. 1. Schematic of the Cr:LiSAF ring laser.

of the Cr:LiSAF crystal, imaged by a combination of spherical and cylindrical optics. The output of each diode was collimated in the diffraction-limited (DL) direction by an 8-mm focal-length spherical lens and, for most of the experiments, was expanded in the non-diffraction-limited (NDL) direction by a  $6\times$  cylindrical telescope. Each pump beam was focused through a 10-cm radius-of-curvature spherical meniscus mirror into the Cr:LiSAF crystal by a 75-mm focal-length spherical lens. Using a Spiricon LBA-100 beam profiler, we measured the pump beam diameter in air ( $1/e^2$  points) to be  $190\ \mu\text{m}$  (NDL)  $\times$   $50\ \mu\text{m}$  (DL). The calculated TEM<sub>00</sub>-mode diameter at the center of the crystal was  $140\ \mu\text{m}$  (NDL)  $\times$   $100\ \mu\text{m}$  (DL). In spite of the pump's overfilling this mode in the NDL direction, when we aligned the Cr:LiSAF laser for maximum output the device showed no sign of oscillation in higher-order transverse modes. When we operated the laser in a standing-wave configuration with only the crystal present in the cavity, the output power at 859 nm was 137 mW for 700 mW of absorbed pump power (Fig. 2). For the ring configuration at the same pump level, the sum of the bidirectional output power was 102 mW. In both configurations the slope efficiency based on absorbed power was 25%, compared with the maximum of 53% set by the combination of the pump defect and the efficiency reduction by excited-state absorption.<sup>6,8</sup>

We tried several types of optical diodes in an attempt to achieve unidirectional operation of the ring. We were not able to obtain high-power ( $>15\text{-mW}$ ) unidirectionality with SF-2 glass as the Faraday element or with a device that minimized insertion loss through the use of optically contacted left- and right-handed crystal quartz.<sup>10</sup> The optical diode that worked used a 4-mm-thick Brewster-cut TGG rhomb as the Faraday material and a 0.264-mm-thick crystalline quartz plate (cut for propagation down the  $c$  axis, oriented at the Brewster angle) as the compensating optical rotator. The diode provides  $3^\circ$  of optical rotation at 850 nm in the backward direction, yielding a differential optical loss of 2.3%. At 700 mW of absorbed pump power and with the birefringent filter and étalon inside the cavity the bidirectional ring output power loss was less than 5%. With the optical diode added to the cavity the Cr:LiSAF laser was unidirectional, but the output power and slope efficiency were reduced to 32 mW and 9%, respectively (Fig. 2). Based on further slope efficiency measurements, we calculated the total loss that was due to the optical diode to be  $\sim 0.7\%$  (approximately equal to the transmission of the output coupler). By removing the quartz plate and the magnet we determined that half the loss was from absorption and scatter in the TGG rhomb. The remainder was presumably from Fresnel losses in the optical diode. The minimum Fresnel loss, based on  $3^\circ$  of rotation, is 0.14%, and we attributed the observed value to residual misalignment among the birefringent filter plates, the optical diode, and the laser crystal.

We used a 2-GHz free-spectral-range confocal interferometer scanning at 10 Hz to characterize the longitudinal-mode structure of the output. The longitudinal-mode spacing of the ring laser was 256 MHz, and the interferometer resolution

was sufficient for us to determine when the laser was operating single frequency. With the laser emitting 24 mW at 853 nm, we accumulated 100 scans (10 s) with a storage oscilloscope (Fig. 3). Figure 3 shows single-frequency operation with a resolution-limited linewidth of approximately 40 MHz and no evidence of additional modes. To estimate frequency stability, we reduced the time per division by a factor of 5 on the storage oscilloscope time base and accumulated 100 scans under the same conditions as in Fig. 3. Figure 4 shows the center-frequency stability to be at least 15 MHz over the 10-s accumulation time, as some drift of the interferometer may have taken place. It should be noted that the laser was operated open to the air without any shielding from air currents or dust. We would expect the passive frequency stability to improve significantly in an enclosed configuration. As a simple measure of amplitude noise, we used a high-speed ( $<10\text{-ns}$  rise time) silicon detector to monitor the output of the ring laser. The peak-to-peak amplitude noise was approximately 1% and was dominated by frequencies between 15 and 25 kHz. We observed occasional 10–20-ms-long

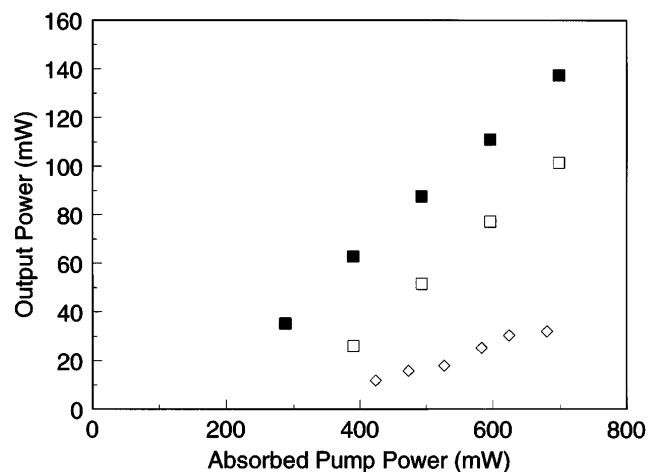


Fig. 2. Input-output data for the Cr:LiSAF laser operating in standing-wave (filled squares), bidirectional ring (open squares), and unidirectional ring (open diamonds) configurations.

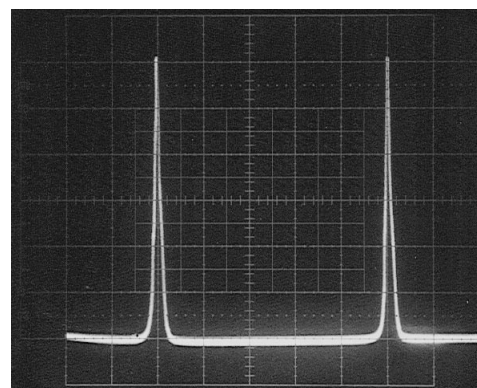


Fig. 3. Scanning confocal interferometer trace (400 MHz/division) of the ring laser emitting 24 mW of power at 853 nm. The scan rate was 10 Hz, and the accumulation time was 10 s.

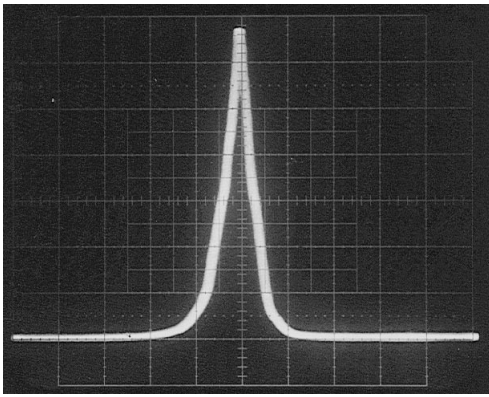


Fig. 4. Scanning confocal interferometer trace (80 MHz/division) taken under the same conditions as the trace shown in Fig. 3.

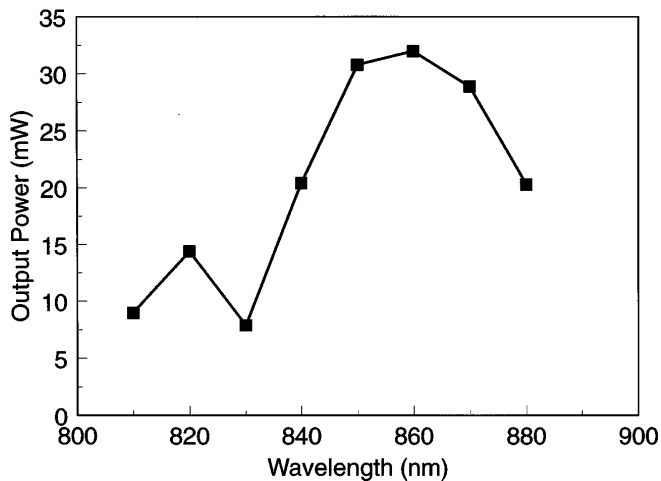


Fig. 5. Tuning curve for the single-frequency Cr:LiSAF ring laser (710-mW absorbed pump power). At 870 nm, the ring operated bidirectionally and multilongitudinal mode; at the other points, the output was single frequency.

fluctuations in power, which we attributed to dust particles.

In Fig. 5 we have plotted the ring laser output power as a function of wavelength at maximum (700 mW) pump power; we found the output to be a single frequency except for wavelengths between 862 and 874 nm, where the ring operated bidirectionally and in multiple longitudinal modes. We attributed this behavior, along with the 830-nm dip in the tuning curve, to imperfect alignment of the three polarization-sensitive intracavity elements (birefringent filter, laser crystal, optical diode). The tuning range was limited at the short-wavelength end by the onset of absorption in the Cr:LiSAF crystal and at the long-wavelength end by the mirror coatings. (In other experiments,

with appropriate mirror coatings, we have operated cw Cr:LiSAF standing-wave lasers at wavelengths as long as 960 nm.) As a final experiment, we increased the magnification of one of the  $6\times$  cylindrical telescopes to  $12\times$  to achieve a better match between the pump spot and the cavity mode in the NDL direction. As a result, the single-frequency output power rose to 43 mW at 849 nm.

In conclusion, we have demonstrated a diode-pumped, single-frequency Cr:LiSAF ring laser that can be tuned from 810 to 860 nm. The maximum output power was limited primarily by the insertion loss of the optical diode, which was designed for use with higher-gain Ti:sapphire lasers. Higher slope efficiencies with the pump lasers that we used may be possible with further optimization of the pump focusing optics and the crystal doping level; operation at wavelengths longer than 880 nm should be possible with properly coated optics. Substantially higher single-frequency powers with diode pumping will require not only lower-loss optical diodes but also higher-brightness pump sources, such as injection-locked semiconductor lasers<sup>4</sup> and the recently developed master oscillator/power amplifier devices (SDL, Inc., Model 7350-A6) capable of 0.5-W power levels in diffraction-limited beams.

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