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Highly efficient, low-cost femtosecond Cr³⁺:LiCAF laser pumped by single-mode diodes

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Abstract

We describe efficient continuous-wave (cw) and cw mode-locked operations of a Cr³⁺:LiCAF laser, pumped by inexpensive single spatial mode laser diodes. Up to 280 mW of cw output power was obtained with 570 mW of absorbed pump power, with a corresponding slope efficiency of 54%. Continuous tuning between 765 and 865 nm was demonstrated using a fused silica prism. A semiconductor saturable absorber mirror was used to initiate and sustain stable, self-starting, mode-locked operation. In cw mode locking, the laser produced 72 fs (FWHM) duration pulses, and 1.4 nJ pulse energy, at an average output power of 178 mW. Electrical to optical conversion efficiencies of 7.8% in mode-locked operation and 12.2% in cw operation were demonstrated.

Cr³⁺-doped colquiriite gain media such as Cr³⁺:LiSAF, Cr³⁺:LiSGaF, Cr³⁺:LiSCAF, and Cr³⁺:LiCAF [1,2] are leading candidates for the development of robust, low-cost, femtosecond lasers since they can be directly diode-pumped with widely available laser diodes at 660 nm wavelengths. Possible diode-pump lasers include arrays [3], broad-stripe single-emitter [4,5], and single transverse-mode laser diodes (narrow-stripe diodes) [6–10]. Laser diode arrays can provide pump powers above 10 W but are relatively expensive and have poor beam quality ($M^2 \sim 1000$ along the axis of the array) [3]. The highest power performance to date (500 mW mode-locked output power) from Cr³⁺: colquiriite media was obtained by pumping a Cr³⁺:LiSAF laser with a 15 W laser diode array; however, the asymmetric pump beam limited the overall efficiency of the system, and a specially designed cavity was required to mode match the pump and to reduce heating [3].

In comparison, broad-stripe multimode, single-emitter diodes are cheaper than arrays, have higher beam quality ($M^2 \sim 10$ along the junction axis) [4,5], and can now produce up to 1.5 W at 665 nm (n-Light Photonics). Using five 1 W single-emitter diodes as the pump source, 67 fs, 2.5 nJ pulses with an output power of 300 mW from a Cr:LiCAF laser were recently demonstrated [4]. However, the asymmetric pump mode and thermal loading limited the slope efficiency of the system to $\sim 10\%$ and the electrical to optical efficiency to $\sim 2.5\%$.

Single transverse-mode laser diodes have diffraction-limited beam profiles and can currently produce ~ 100 – 150 mW of output power at very low cost. Early investigations demonstrated the feasibility of using low-cost, single-mode diodes for pumping Cr:LiSAF [6–10]. The nearly symmetric, diffraction-limited beam profiles from single-mode diodes enabled high cw slope efficiencies and high electrical to optical conversion efficiencies. Using four ~ 55 mW single-

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mode diodes as the pump, Agate *et al.* obtained 122 fs, ~ 0.07 nJ pulses with 35 mW of average power from a compact Cr:LiSAF laser, and demonstrated electrical to optical conversion efficiencies of $\sim 4\%$ [8]. Using three 50 mW single-mode diodes to pump a Cr:LiSAF laser with a multipass cavity to scale pulse energies [11], Prasankumar *et al.* obtained 39 fs pulses with 0.75 nJ energies, 6.5 mW of average power at 8.6 MHz repetition rate [10]. To date, single-mode diode pumping of Cr³⁺: colquiriite media has only been applied to Cr:LiSAF, mainly because of the lower scattering losses [12] and slightly higher gain of this medium [3].

In this Letter, we describe a highly efficient, low-cost femtosecond Cr³⁺: LiCAF laser pumped by four ~ 165 mW single-mode laser diodes. In cw operation, up to 280 mW of output power was obtained at ~ 790 nm with 570 mW of absorbed pump power and a slope efficiency of 54%. Mode locking was initiated and sustained with a semiconductor saturable absorber mirror (SESAM) [13], also known as a saturable Bragg reflector (SBR) [14]. In mode-locking experiments, 72 fs, 1.4 nJ pulses with 178 mW of average power was obtained. To the best of our knowledge, this is the highest average power and pulse energy obtained using single-mode diode pumping, and the cw slope efficiency is the highest obtained from any diode-pumped Cr³⁺: colquiriite laser [15]. In addition, an electrical to optical conversion efficiency of 12.2% and 7.8% was demonstrated for cw and mode-locked operation, respectively, which we believe is the highest conversion efficiency ever obtained for a femtosecond solid state laser [8].

Figure 1 shows a schematic of the Cr³⁺: LiCAF laser cavity. Four linearly polarized ~ 660 nm AlGaInP single-mode diodes (D1–D4) with diffraction-limited beam profiles were used as the pump source (HL6545MG, Hitachi), each providing up to ~ 160 – 170 mW, at a drive current of 220 mA (2.6 V), corresponding to a $\sim 28\%$ – 30% electrical to optical conversion efficiency. In total, at this maximum driving current (220 mA), the four diodes required ~ 2.3 W and produced ~ 660 mW of output power. The diodes had an asymmetric beam profile with an aspect ratio of ~ 2 ($\theta_{\perp} \approx 17^{\circ}$, $\theta_{\parallel} \approx 10^{\circ}$), hence cylindrical microlenses were used to obtain a circular beam profile. The diodes were mounted without water cooling, and 4.5 mm focal length lenses were used to collimate the output beams. A polarizing beam splitter (PBS) cube polarization combined pairs of diodes, and two 63 mm focal length lenses focused the pump beams in the crystal from opposite directions.

An astigmatically compensated, x-folded laser cavity was used in the cw experiments (dashed line in Fig. 1). The resonator had two curved pump mirrors (M1 and M2, $R=75$ mm), a flat end mirror (M3), and a flat output coupler (OC). Pump mirrors (M1, M2) had high reflectivity extending from 750 to 850 nm and $>95\%$ transmission at the pump wavelength (~ 660 nm). Arm lengths of 37 cm (OC arm) and 65 cm were used to obtain a laser mode size of ~ 15 μ m inside the Cr:LiCAF crystal. The gain medium was a 2 mm long, Brewster-cut, 10% Cr-doped Cr³⁺:LiCAF crystal mounted with indium foil in a copper holder [4,5]. At the maximum driving current, 630 mW of pump power was incident on the crystal. For the TE polarized pump light, $\sim 10\%$ of the pump light was lost by Fresnel reflection from the crystal surface. The crystal absorbed 97.5% and 84% ($0.9\% \times 93.5\%$) of the incident TM and TE polarized pump lights, respectively, and the total absorbed pump power was ~ 570 mW. Water cooling of the crystal was not required.

For mode-locking experiments, two double-chirped mirrors (DCM-1 and DCM-2) with group velocity dispersion (GVD) of approximately -50 fs² per bounce were used to provide negative dispersion. The estimated total round-trip cavity dispersion was approximately -50 to -100 fs². A SESAM with a low level of nonsaturable loss ($\sim 0.5\%$) was used to initiate and sustain mode locking. More details about this SESAM are reported in [4]. A 75 mm radius of curvature mirror (M4) was used to focus on the SESAM. The SESAM mode-locked laser was self-starting, immune to environmental fluctuations, and did not require careful cavity alignment, enabling turn-key operation.

Figure 2 shows the cw laser performance using 0.5%, 1.95%, and 6% transmission OCs. The cw output wavelength was ~ 790 nm for all OCs. The best cw laser power performance was obtained with the 1.95% OC. Using this OC, the laser produced up to 280 mW of output power with 570 mW of absorbed pump power. The corresponding threshold pump power and the slope efficiency with respect to absorbed pump power were 45 mW and $\sim 54\%$, respectively. The high slope efficiency is due to the extremely low loss optics used in the laser, where the main intracavity loss was from the crystal and was estimated to be $0.2\% \pm 0.1\%$ per single pass. To the best of our knowledge, this is the highest slope efficiency obtained from any diode pumped Cr^{3+} :colquirite laser [15]. The slope efficiencies were obtained with a 10% doped Cr^{3+} :LiCAF crystal and shows that, despite the early indications of concentration dependent parasitic losses and excited state absorption [1,15], slope efficiencies $>50\%$ can still be obtained from highly doped Cr^{3+} :LiCAF samples. By inserting a fused silica prism in the high-reflector arm, the laser could be tuned continuously from 765 to 865 nm using the 0.85% OC.

In mode-locking experiments, different OCs were tried to optimize performance. Although pulses as short as ~ 50 fs [4] could be obtained with lower OCs, the 1.9% OC gave the maximum output power. Figure 3 shows the variation of laser output power and laser dynamics with absorbed pump power, using the 1.95% OC. The laser operated in cw mode for absorbed pump powers up to ~ 225 mW and generated Q -switched mode-locked pulses for pump powers between ~ 225 and ~ 500 mW (Q -switched ML in Fig. 3). Stable cw mode locking was obtained for pump powers above ~ 500 mW (cw ML). Figure 4 shows the spectra and autocorrelation trace taken with the 1.9% OC at the pump power of ~ 570 mW. The laser produced 72 fs pulses (assuming sech^2 pulses) with 178 mW average power and 10.3 nm spectral bandwidth near 800 nm at 127 MHz (~ 1.4 nJ pulse energy). The time–bandwidth product was ~ 0.35 , close to the transform limit of 0.315 for sech^2 pulses. To our knowledge, these are the highest average powers and pulse energies obtained to date from single-mode diode-pumped Cr^{3+} :colquirite lasers. For the cw mode-locked operation, the optical-to-optical conversion efficiency was $\sim 28\%$ (178 mW/660 mW), and the electrical-to-optical conversion efficiency was $\sim 7.8\%$ (178 mW/2.3 W). We believe this is the highest electrical to optical conversion efficiency obtained to date from a femtosecond laser [8].

In conclusion, we demonstrate efficient cw and cw mode-locked operation of a Cr^{3+} :LiCAF laser pumped by inexpensive single-mode laser diodes. Up to 280 mW of output power and tunability between 765 and 865 nm was demonstrated in cw experiments. Using a SESAM for mode locking, the laser generated pulses of 72 fs duration with 178 mW of average output power. We believe the reported electrical to optical conversion efficiencies are the highest to date obtained from a femtosecond solid-state laser [8]. These results show that with the advent of high-power single-mode diode technology, economical femtosecond Cr^{3+} :colquirite laser systems can be developed for a variety of femtosecond laser applications.

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Fig. 1.
(Color online) Schematic of the single-mode diode-pumped $\text{Cr}^{3+}:\text{LiCAF}$ laser. Dashed line shows the cw cavity.

Fig. 2.
(Color online) cw efficiency curves for the single-mode diode-pumped $\text{Cr}^{3+}:\text{LiCAF}$ laser taken with the 0.5%, 1.95%, and 6% OCs.

Fig. 3.
(Color online) Efficiency curve for the Cr³⁺:LiCAF laser in different operating regimes with the 1.95% OC.

Fig. 4.
(Color online) Measured spectra and autocorrelation trace for the 72 fs, 1.4 nJ pulses with 178 mW of average output power taken using the 1.9% OC.