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# Generation of 15-nJ pulses from a highly efficient, low-cost multipass-cavity Cr<sup>3+</sup>:LiCAF laser

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## Abstract

We describe the generation of enhanced pulse energies and intensities using an extended multipass-cavity (MPC) Cr<sup>3+</sup>:LiCAF laser, pumped by inexpensive, single spatial mode laser diodes. A semiconductor saturable absorber was used to initiate and sustain stable mode-locked operation. The MPC reduced the pulse repetition rate to the ~10 MHz level, scaling pulse energies and intensities. With only 540 mW of absorbed pump power, 98-fs pulses with energies of 9.9 nJ and peak powers of ~101 kW, corresponding to 95 mW of average power at a repetition rate of 9.58 MHz, were generated. By increasing the intracavity negative dispersion, 310-fs pulses with energies of 15.2-nJ and peak powers of ~49 kW, corresponding to 160 mW of average power at 10.51 MHz repetition rate, were also generated. These results demonstrate that low cost MPC Cr<sup>3+</sup>-doped colquiriite lasers can generate pulse energies and intensities comparable to those achieved by more expensive Ti:Sapphire laser technology.

**OCIS Codes:** 140.3460: Lasers; 140.4050: Mode-locked lasers; 140.3580: Lasers, solid-state; 140.3480: Lasers, diode pumped; 140.3600: Lasers, tunable; 140.5680: Rare earth and transition metal solid-state lasers

Cr<sup>3+</sup>-doped colquiriite gain media such as Cr<sup>3+</sup>:LiCAF, Cr<sup>3+</sup>:LiSAF and Cr<sup>3+</sup>:LiSGaF can be directly diode-pumped near 650 nm and enable the development of low-cost and highly efficient lasers operating near 800 nm [1-11]. Furthermore, the broad gain bandwidths of these media enable the generation of pulses as short as 10 fs [5, 7]. Possible laser diode pump sources include diode arrays [4], broad-stripe single-emitter diodes [3, 7-9, 11] as well as single transverse-mode diodes [6, 10, 11]. The peak powers obtainable from colquiriite media can be increased by scaling the output energy and/or reducing the pulsewidths. To date, the highest peak power obtained from a diode pumped Cr<sup>3+</sup>:Colquiriite laser was ~45 kW (50 fs, 2.27 nJ pulses at 150 MHz), using a 15-W laser diode array to pump a Cr:LiSAF laser [4]. We recently reported the generation of 67-fs pulses with energies and peak powers up to 2.5 nJ and ~37 kW, respectively, from a Cr<sup>3+</sup>:LiCAF laser pumped by five 1-W broad-stripe diodes [9]. Using four, low-cost, single-mode pump diodes with a total absorbed power of 570 mW, 72-fs pulses were generated at a repetition rate of 127 MHz, corresponding to pulse energies of 1.4 nJ and peak powers of ~19.5 kW [10].

Although higher peak powers can be obtained with multimode diode pumping [4, 9], single mode pumping has the advantages of lower cost, better matching between pump and laser modes, significantly lower lasing thresholds, reduced thermal effects and higher efficiency [10, 11]. For example, mode-locked optical-to-optical conversion efficiencies of ~28% have been demonstrated with single-mode diode pumping [10], whereas only 6% and 7.5% efficiency could be obtained with arrays [4], and broad-stripe single-emitter diodes, respectively [9]. Furthermore, for single mode diode pumping, no cooling is needed for the pump diodes or laser crystal, enabling compact and portable systems. However, since the pump powers available from single mode diodes are limited, pulse energies are lower. To overcome this limitation, the output energy can be scaled up by extending the laser cavity length to lower the pulse repetition rate. If the average output power is nearly constant,

lowering the repetition rate leads to higher output energies provided that additional dispersion is introduced to balance the nonlinearities. Multipass cavities (MPC) can be used to extend the cavity lengths with a relatively compact mirror configuration [6, 12]. MPCs have previously been applied to a Cr:LiSAF laser to obtain 39-fs, 0.75 nJ pulses at a repetition rate of 8.6 MHz [6]. The pulse energy obtained in [6] was limited by the fact that high-power single-mode diodes and low-loss resonator optics were not available at the time.

In this Letter, we describe the generation of enhanced pulse energies and intensities using a low cost, MPC femtosecond Cr<sup>3+</sup>:LiCAF laser pumped by four ~150-mW single-mode laser diodes. Mode locking was initiated and sustained with a semiconductor saturable absorber mirror (SESAM) [13], also referred to as a saturable Bragg reflector (SBR) [14], which enabled stable and robust mode-locked operation. In mode-locked operation, 98-fs, 9.9-nJ pulses with a peak power of ~101 kW, corresponding to 95 mW of average power were obtained at 9.58 MHz repetition rate, were generated. In addition, 310-fs, 15.2-nJ pulses with a peak power of ~49 kW, corresponding to 160 mW of average power at 10.51 MHz repetition rate, were generated using increased intracavity dispersion. The optical-to-optical conversion efficiency was 15.8% and 26.7%, for the 98-fs and 310-fs configurations, respectively. To the best of our knowledge, these are the highest peak powers and pulse energies obtained from any Cr<sup>3+</sup>:Colquiriite laser to date. The pulse energies and peak intensities are comparable to femtosecond Ti:Sapphire lasers operating with ~1 W of average output powers. This suggests that diode pumped MPC Cr<sup>3+</sup>:Colquiriite lasers can be an attractive low cost alternative to more expensive Ti:Sapphire technology for applications in nonlinear optics, pump probe spectroscopy, amplifier seeding and multiphoton microscopy [15].

The demonstration of MPC cavities using Cr<sup>3+</sup>:LiCAF is challenging because its gain is significantly lower than that of Ti:Sapphire. Therefore, low loss mirrors, with reflectivity

approaching 99.99%, must be used. In this study, we focused on Cr:LiCAF because it enables the generation of shorter wavelengths than Cr:LiSAF and Cr:LiSGaF and also affords higher energy storage. The results here establish the feasibility for MPC pulse energy scaling in Cr:LiSAF and Cr:LiSGaF which have higher gains and are less sensitive to intracavity loss.

Figure 1 shows the experimental setup for the short and the extended-cavity (MPC) Cr<sup>3+</sup>:LiCAF laser. Four, linearly-polarized, ~660-nm single-mode diodes, costing only \$150 each, (VPSL-0660-130-X-5-G, Blue Sky Research) were used as the pump (D1-D4). The diode outputs were collimated using 4.5-mm focal length lenses, coupled via polarizing beam splitter cubes (PBSs), and then focused inside the crystal using 65-mm focal length lenses. The short cavity was a standard astigmatically compensated, x-fold laser resonator, similar to that described in [10].

The continuous-wave (cw) resonator for the short cavity consisted of two curved pump mirrors (M1 and M2, R=75 mm), a flat end high reflector (M4), and a flat output coupler (OC). Pump mirrors (M1-M2) had a transmission >95% at the pump wavelength (~660-nm) and had a reflectivity >99.9% from 740 to 860 nm. Arm lengths of ~35 cm (OC arm) and ~50 cm were used to obtain an estimated laser mode size of ~20  $\mu\text{m}$  x 28  $\mu\text{m}$  (sagittal x tangential) inside the Cr:LiCAF crystal, which has a refractive index of  $n\sim 1.4$ . The gain medium was a 2.5-mm-long, 1.5-mm-tall, Brewster-cut, 11% Cr-doped Cr<sup>3+</sup>:LiCAF crystal (from VLOC, Inc.). The crystal absorbed >98% of the incident pump for both polarizations, corresponding to a total of 540 mW of pump power. In cw laser experiments with the short cavity, the highest output power was 271 mW, obtained using a 0.85% output coupler, with a slope efficiency of 54%. Measuring the lasing thresholds with 7 different output couplers, we estimated the round trip loss of the short cavity to be  $0.43 \pm 0.1\%$ .

The cavity length was extended by removing the high reflecting end mirror M4 and adding a q-preserving MPC consisting of a flat (M5) and curved (M6, R=4 m) high reflector.

The separation between the MPC mirrors was 1 m, resulting in an angular advance of  $60^\circ$  per round trip on each MPC mirror. Beam injection and extraction were achieved by using notches in the mirrors. Because of the notches on the MPC mirrors, 6 full round trips were not completed. To complete the 6 round trips, which are required to preserve the q-parameter of the returning beam, we used an additional curved mirror (M7, R=4m) placed after M6. The beam exiting M6 was folded by M7 and retro-reflected by a flat end high reflector (M8) at a distance of 1 m from M7. This arrangement preserves the beam q-parameter, as described previously [12]. From the cw lasing data, the insertion loss of the MPC was estimated to be  $0.35\% \pm 0.1$ . With the addition of the MPC, the high reflector arm length increased from  $\sim 0.5$  m to  $\sim 12.5$  m ( $0.5$  m +  $2 \times 6 \times 1$  m), which reduced the repetition rates to  $\sim 10$ - $11$  MHz. Finally, the optimum output coupling for the extended cavity increased to  $\sim 3\%$ , where we obtained 213 mW of cw output power with a slope efficiency of 48%. Note that, despite the additional 24 bounces introduced by the MPC cavity, the cw power only decreased from 271 mW to 213 mW, which was possible with the use of low loss MPC mirrors (R $\sim 99.99\%$ ).

For mode-locked operation, additional mirror bounces (6 bounces on M9 and M10 and 2 bounces on M11) were used to provide the necessary group velocity dispersion (GVD). Except for the pump mirrors, output coupler, the GTI mirror (M11) and M12, all the optics used in the cavity were chirped mirrors with a GVD of  $\sim -40 \pm 5$  fs<sup>2</sup> per bounce from 730 to 870 nm. The GTI mirror (M11) had a GVD of  $\sim -550 \pm 100$  fs<sup>2</sup> per bounce from 775 to 815 nm. Mirrors M9-M11 were required to provide additional negative GVD, since the dispersion provided by the MPC mirrors was not sufficient. The additional mirrors, M9 to M11, could be eliminated and a simpler cavity design achieved if higher dispersion MPC mirrors with a GVD of  $\sim -80$ fs<sup>2</sup> were used. The estimated total round-trip cavity dispersion was  $\sim -2000 \pm 300$  fs<sup>2</sup> (775-815 nm). A SESAM/SBR with a low nonsaturable loss ( $\sim 0.5\%$ ) was used to initiate and sustain mode locking [9, 10]. A curved mirror (M12) with R=60 cm was used to

focus onto the SESAM/SBR. Mode locking was not self starting and required slight tapping on the SESAM/SBR holder, but once initiated, the mode-locked laser was immune to environmental fluctuations. When mode-locked at the full pump power ( $\sim 540$  mW), the laser produced 9.92 nJ pulses with 95 mW average power at a 9.58 MHz repetition rate (using a 2.4% output coupler). Figure 2 shows the measured optical spectra and autocorrelation. The main part of the spectra centered around 782.7 nm has a FWHM of  $\sim 6.75$  nm, which supports  $\sim 95.5$  fs Fourier limited pulses, assuming a  $\text{sech}^2$  pulse shape. The autocorrelation has  $\sim 151.3$  fs FWHM, corresponding to a  $\sim 98$  fs pulse for  $\text{sech}^2$  pulse shape. The time bandwidth product was  $\sim 0.323$ , close to the transform limit of 0.315. The corresponding peak power of the pulses was  $\sim 101$  kW. The side lobe in the spectra around 809 nm was due to GVD oscillations introduced by the GTI mirror, and similar oscillations were also observed with the GTI mirror in the short cavity. Despite this limitation, the GTI mirror has the advantage that it can provide large dispersion. Achieving similar amounts of dispersion ( $\sim -550$  fs<sup>2</sup>) from standard DCMs would require 13 to 14 bounces. This would increase loss and limit pulse energies, especially when using a low-gain medium such as Cr:LiCAF

Pulse energies were limited by the onset of modelocking instabilities which produced wings on the autocorrelation (due to multiple pulsing). We believe that these instabilities arise from two photon absorption (TPA) in the SESAM/SBR. Increasing the spot size on the SESAM/SBR reduces the two photon absorption, but also trades off the effective saturable absorber cross section, making initiation of modelocking more difficult. Operating the laser with longer pulses reduces the two photon absorption. A re-designed SESAM/SBR with a larger dynamic working range, should enable the generation of pulses with higher peak powers.

When the dispersion of the cavity was increased to  $\sim -4000 \pm 500$  fs<sup>2</sup> by using more GTI bounces, we obtained 310-fs, 15.2 nJ pulses with peak powers of  $\sim 49$  kW, corresponding

to 160 mW average power at 10.51 MHz repetition rate. For this case, a curved mirror with  $R = 15$  cm was used to focus on the SESAM/SBR, and mode locking was self starting. Figure 3 shows the spectrum and the autocorrelation, taken with the 2.4% output coupler at full pump power ( $\sim 540$  mW). This time the spectrum was narrower and was not affected by the nonlinear GVD from the GTI mirror, so a smooth spectrum could be obtained. The time bandwidth product was  $\sim 0.325$ , close to the transform limit of 0.315 for  $\text{sech}^2$  pulses.

In conclusion, enhanced pulse energies and intensities were generated using an MPC  $\text{Cr}^{3+}$ :LiCAF laser pumped by single-mode laser diodes. Pulse energies of 10 to 15 nJ and peak intensities of 50 to 100 kW were achieved which, to our knowledge, are the highest generated from Cr:Colquiriite lasers to date. The MPC produced a  $\sim 10\times$  enhancement in pulse energy by reducing laser repetition rate from 100 MHz to 10 MHz. Many applications in nonlinear optics depend on pulse energy and intensity. The reduced repetition rate may also be helpful for applications which are sensitive to average power or thermal effects, such as pump probe spectroscopy or multiphoton microscopy. The pulse energies achieved here are comparable to those obtained from femtosecond Ti:Sapphire lasers at 1 W average power. These results demonstrate that single-mode diode pumped MPC  $\text{Cr}^{3+}$ :Colquiriite lasers can be an attractive and low cost alternative to Ti:Sapphire technology.

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cost and highly efficient Cr:LiCAF laser," *Optics Express*, vol. 16, pp. 20848–20863, 2008.

## Figure Captions

Figure 1: (Color online) Schematic for the short and extended-cavity (MPC) single mode diode pumped Cr<sup>3+</sup>:LiCAF laser.

Figure 2: (Color online) Optical spectra and background-free intensity autocorrelation for the 98-fs, 9.92 nJ pulses (~101 kW peak power), corresponding to 95 mW average output power at 9.58 MHz repetition rate.

Figure 3: (Color online) Optical spectra and autocorrelation for the 310-fs, 15.2-nJ pulses (~49 kW peak power), corresponding to 160 mW of average output power at 10.51 MHz repetition rate.

**Figure 1**

(two column width)

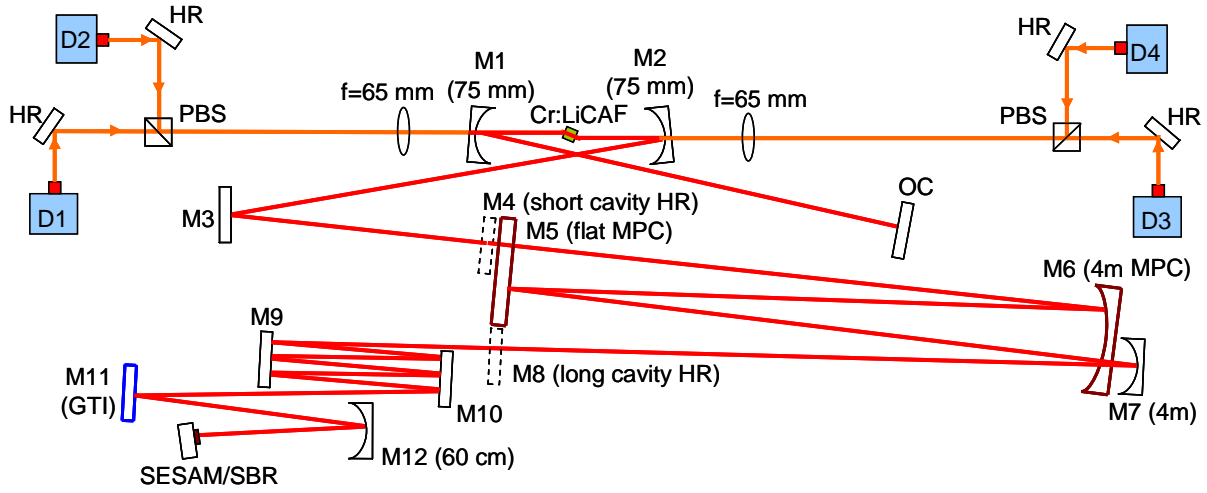
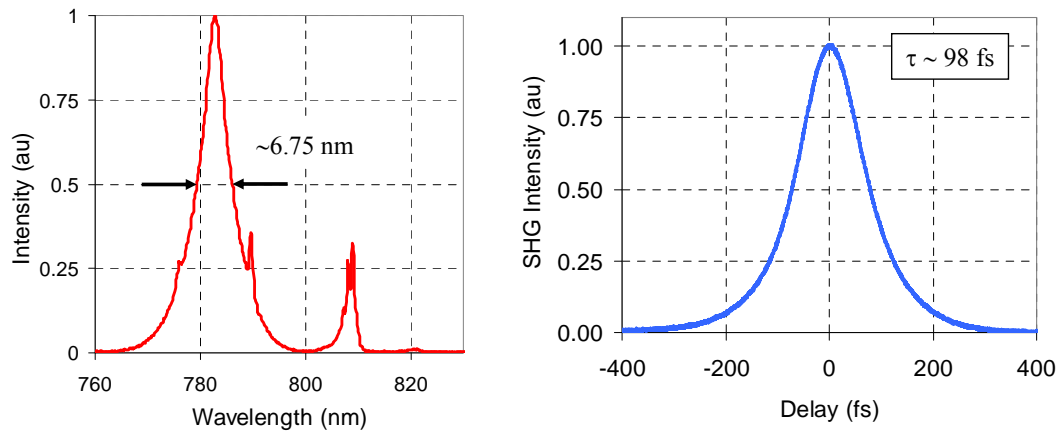


Figure 2





**Figure 3**

