# Mode-locked all-solid-state diode-pumped Cr:LiSAF laser

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A diode-pumped mode-locked Cr:LiSAF laser is demonstrated for what is to our knowledge the first time. Active mode locking, with an acousto-optic modulator, and resonant passive mode locking, with a multiple-quantum-well absorber in an external cavity, have both yielded cw trains of picosecond pulses.

Titanium-doped sapphire ($Ti:Al_2O_3$) lasers can routinely generate tunable femtosecond pulses in the near infrared by exploiting self-focusing or Kerr-lens mode locking[1-7] (KLM), and recently pulse durations approaching 10 fs have been achieved.[6,7] Unfortunately, the requirement for an argon-ion pump laser makes $Ti:Al_2O_3$ lasers impractical for many applications. The development of $Cr^{3+}:LiSrAlF_6$ (Cr:LiSAF), however, offers a vibronic laser medium with an emission band comparable with that of $Ti:Al_2O_3$, which has absorption bands and an upper-state lifetime compatible with diode pumping.[8] Mode locking of this laser medium has already been achieved by KLM with a number of different pulse-forming mechanisms to initiate the mode locking by increasing the intracavity intensity. An acousto-optic modulator was employed to yield pulses as short as 50 fs,[9] and a saturable-absorber dye was employed to obtain pulses as short as 33 fs in a laser cavity with low-dispersion F2 prisms.[10] Recently a solid-state laser oscillator was demonstrated that uses an intracavity multiple-quantum-well (MQW) absorber to initiate mode locking, and this approach has yielded transform-limited pulses as short as 93 fs for less than 500 mW of absorbed pump power at 488 nm.[11] This pump power is compatible with the output powers of commercially available 670-nm laser diodes, and so an all-solid-state femtosecond Cr:LiSAF laser should be possible. It should be noted, however, that the currently available Cr:LiSAF laser crystals are able to tolerate only a few watts ($\lesssim 4$ W) of pump power before they are damaged, so it appears unlikely that this laser medium will deliver the same high average mode-locked output powers as $Ti:Al_2O_3$ lasers.

Diode pumping of Cr:LiSAF has been demonstrated at ~670 nm (Refs. 12 and 13) and in the wing of the absorption profile near 760 nm,[14] but to date these results have been for cw lasers only. We report here what are to our knowledge the first results on the mode locking of diode-pumped Cr:LiSAF lasers. The principal difficulty is that the beam quality of the diodes is poor (i.e., noncircular, multilobed, and far from diffraction limited) compared with that from an ion laser. This is likely to make energy extraction and KLM relatively difficult to achieve. We note that such work has been done with a Nd:YAG laser.[15] Our diodes (from McDonnell Douglas) were of 500-mW output power at approximately 665 nm and had an active stripe width of 160 $\mu$m. They were multimode and highly divergent, giving an uncollimated elliptical beam of aspect ratio ~8:1. After collimation these diodes were initially combined in a polarizing beam splitter. The resulting composite beam of ~630-mW power was then coupled into a graded-index fiber of 50-$\mu$m diameter (single mode at 1.55 $\mu$m) and collimated to form a circular pump beam of ~270 mW.

Initially we constructed the cw laser that is shown in Fig. 1(a). The 2% doped Cr:LiSAF rod (from Lightning Optical Corporation) was plane at one end and Brewster angled at the other, with a center beam path length of 9 mm. The Brewster angle was cut such that the laser radiation was polarized perpendicularly to the crystallographic *c* axis. A thin dielectric mirror, $M_1$, of 100% reflectivity at 830 nm and 80% transmission at 670 nm, was optically contacted onto the plane face of the laser rod, and the pump beam was focused through this mirror by a lens of 25-mm focal length, $L_1$. An astigmatically compensated cavity was formed by a curved mirror, $M_2$, of 100-mm radius of curvature and a plane mirror $M_3$, through which the output was obtained.

The laser threshold was 150 mW with mirror $M_3$ as a nominal 100% reflector at the laser wavelength, and the laser was tuned from 799 to 860 nm by a prism used as the tuning element. Using a 1% output coupler as $M_3$ increased the threshold to 200 mW, and we obtained as much as 2 mW of output power. In later experiments the graded-index fiber was abandoned, and the cavity mode itself was the only spatial filter of the pump beam. This yielded laser thresholds as low as 70 mW, which increased to 86 mW with the 1% output coupler in the cavity. Output powers as high as 10 mW were

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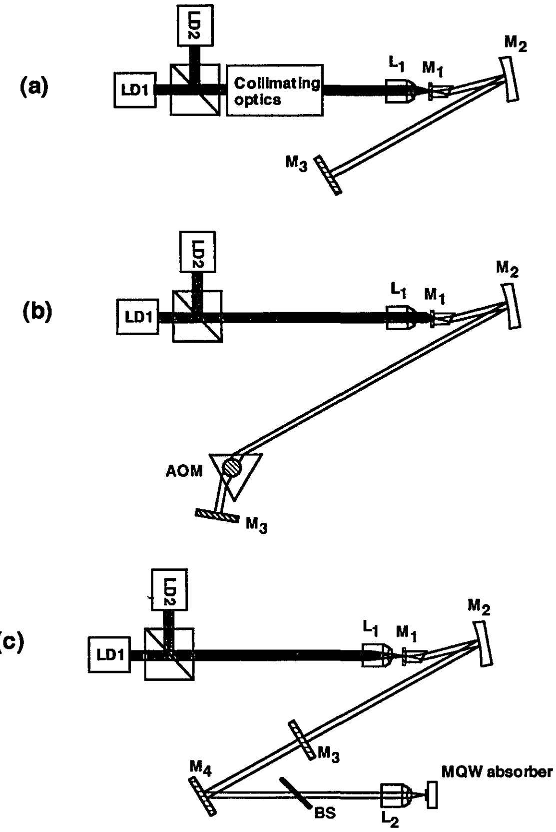


Fig. 1. (a) Schematic of the cw Cr:LiSAF laser, (b) schematic of the actively mode-locked Cr:LiSAF laser, (c) schematic of the resonant passively mode-locked Cr:LiSAF laser. LD's, laser diodes; L's, lenses; M's, mirrors; BS, beam splitter.

then obtained with a maximum slope efficiency of 3%. With a 2.5% output coupler the threshold increased to 165 mW with as much as 6 mW of output power obtained and a maximum slope efficiency of 2.8%.

Active mode locking was demonstrated with a Spectra-Physics acousto-optic modulator (AOM) at a resonant frequency of ~40.4 MHz, as shown in Fig. 1(b). Again, $M_3$ was a 99% broadband reflector centered at 800 nm, through which the output was obtained. For ~1 W of rf power to the modulator, the cw mode-locked pulse trains shown in Fig. 2 were observed. These pulses were of ~300-ps duration, and the laser was operating very close (~10%) to threshold. Average output powers of ~1 mW were measured. It is anticipated that with more pump power and an optimized cavity, this laser should yield pulses of approximately tens of picoseconds or, with KLM, of sub-100-fs duration.

To demonstrate an all-solid-state passively mode-locked laser, we employed resonant passive mode locking[4,16] with the MQW absorber of Ref. 11 in a resonant external cavity, as shown in Fig. 1(c). The 1% output coupler was employed to permit ~5 mW of laser radiation to be focused onto the retroreflecting MQW absorber structure by a 20× microscope objective. Stable cw mode-locked pulse trains at 250 MHz as short as ~70-ps duration were observed, as measured with a sampling streak camera, and are shown in Fig. 3. Outputs were taken either through $M_4$ (~0.5% transmitting) or off the intracavity beam splitter. The output power taken through $M_4$ was 2 mW. This laser can potentially deliver subpicosecond pulses at repetition rates as high as a gigahertz if sufficient diode pump power can be coupled into the gain medium, promising a robust and compact all-solid-state source of ultrashort pulses in the tuning range from ~750 to ~950 nm.

In conclusion, we have demonstrated what is to our knowledge the first all-solid-state diode-pumped tunable mode-locked laser. Using Cr:LiSAF, pumped by InGaAlP laser diodes, we have demonstrated both active mode locking and resonant passive mode locking and have generated cw trains of picosecond pulses. From our earlier research[11] we note that if we can couple ~500 mW of pump light into the cavity mode of the resonator, then sub-100-fs pulse generation should be routinely possible with the MQW absorber located inside the laser cavity. We also note that Cr:LiSAF is an attractive medium for regenerative amplification and that ~1 W of diode pump power should permit the amplification of 100-fs pulses to the microjoule level at repetition rates of ~10 kHz.[17] This would permit an extremely compact and portable all-solid-state femtosecond laser system to be developed for a wide range of applications.

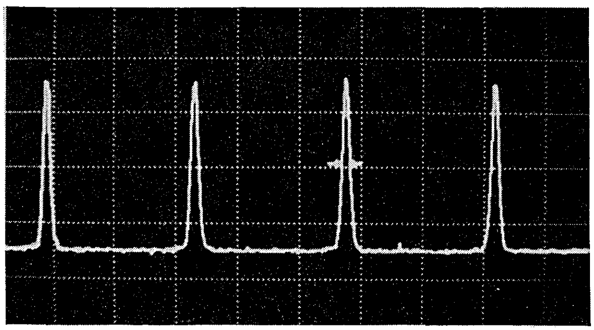

Fig. 2. Sampling streak camera oscillogram (5 ns/division) of pulses from the actively mode-locked Cr:LiSAF laser.

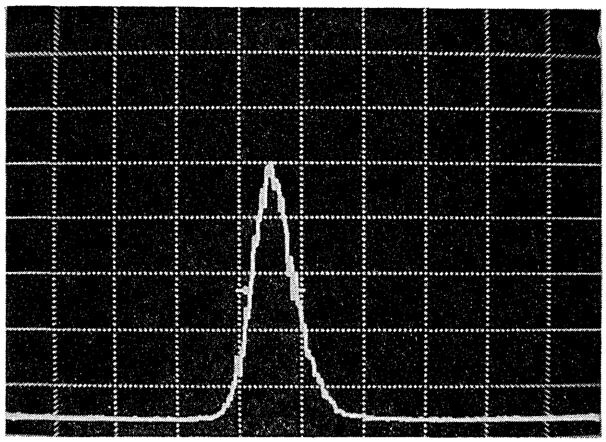

Fig. 3. Sampling streak camera oscillogram (100 ps/division) of pulses from the passively mode-locked Cr:LiSAF laser with the MQW absorber in a resonant external cavity.

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