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# Widely-Tunable Femtosecond Operation of Cr:LiSAF Lasers using Broadband Saturable Bragg Reflectors

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**Abstract:** We describe a low-cost diode-pumped Cr:LiSAF laser, mode-locked using a broadband saturable Bragg reflector. The laser produces continuously tunable sub-200-fs pulses from 800 nm to 905 nm.

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**OCIS codes:** (140.3600) Lasers, tunable; (140.3480) Lasers, diode pumped; (140.4050) Mode-locked lasers

Lasers having Cr<sup>3+</sup>-doped colquiriite gain media (Cr:LiCAF, Cr:LiSAF and Cr:LiSGaF) were first demonstrated by Payne et al. [1] in late 1980s. These media can be directly diode-pumped around 650 nm, providing a potential low-cost alternative to femtosecond Ti:Sapphire lasers. Among Cr:Colquiriites, Cr:LiSAF has the highest peak emission cross section, highest gain and broadest tuning range [2]. A continuous-wave tuning range from 782 nm to 1042 nm was recently demonstrated from a low-cost diode-pumped Cr:LiSAF laser [2]. For Cr:LiSAF lasers, tuning ranges of 809 nm to 910 nm [3], and 835 nm to 910 nm [4] have been demonstrated with femtosecond pulses, using Kerr-lens mode-locking (KLM). However, the nonlinear refractive index ( $n_2$ ) values of Cr:Colquiriites are small; hence, long-term stable and robust KLM operation is difficult to achieve.

As an alternative to KLM, femtosecond pulses can be initiated using semiconductor saturable absorber mirrors (SESAMs) [5], which is also referred as saturable Bragg reflectors (SBRs) [6]. Advantages of using SESAMs/SBRs instead of KLM include self-starting mode-locked operation, immunity to environmental fluctuations and reduced cavity alignment requirements. Typically, in standard SESAMs/SBRs, absorbers are integrated onto AlGaAs/AlAs Bragg mirrors, and the low-index contrast ( $\Delta n \sim 0.5-0.6$ ) between the layers results in narrow bandwidth mirrors ( $\sim 70$  nm,  $R > 99.5\%$ ). Due to this bandwidth limitation from the low-index contrast Bragg mirrors, tuning ranges from the SESAM/SBR mode-locked Cr:LiSAF lasers were restricted to about 50 nm [7].

In this work, we describe a low-cost, diode-pumped Cr:LiSAF laser with  $>100$  nm of mode-locked tuning range. A broadband SESAM/SBR was used to initiate and sustain mode-locking. Dispersion-compensating mirrors (DCM) optimized for the Cr:LiSAF gain media enable a relatively smooth group velocity dispersion (GVD) over the whole tuning range. A specially-designed birefringent (BR) plate was used for tuning. By just rotating the BR plate, the central wavelength of the mode-locked pulses is tuned continuously from 800 nm to 905 nm (a 105 nm tuning range). The pulses are nearly transform-limited over the entire tuning range, with an average pulsewidth and average pulse energy of  $\sim 140$  fs and  $\sim 2$  nJ, respectively. To the best of our knowledge, this is the broadest tuning range reported for any SESAM/SBR mode-locked femtosecond solid state laser.

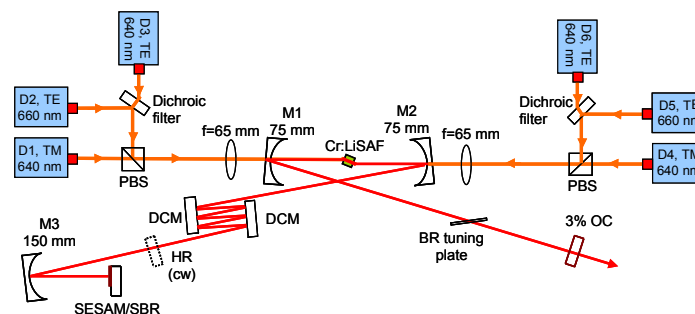


Fig. 1. Schematic of the single-mode diode-pumped Cr:LiSAF laser system that was used in femtosecond tuning experiments.

A schematic of the single-mode diode-pumped Cr:LiSAF laser that was used in femtosecond tuning experiments is shown in Fig. 1. The gain medium was pumped by four 640 nm and two 660 nm linearly-polarized, single-mode diodes (D1-D6) with circular outputs. A maximum pump power of  $\sim 150$  mW and  $\sim 200$  mW was available from the 640 nm and 660 nm diodes, respectively. The output of the diodes was first collimated by aspheric lenses and then combined using polarizing beam splitting (PBS) cubes and dichroic filters. Two 65-mm focal length lenses focused the pump beams in the Cr:LiSAF crystal. The 6-mm long Cr:LiSAF crystal has a Cr concentration of 1.5% and absorbed  $>99\%$  and  $>77\%$  ( $0.9 \times 85\%$ ) of the incident TM- and TE-polarized pump at 640 and 660 nm respectively. An astigmatically-compensated, x-folded laser cavity, with 75 mm radius of curvature (roc) pump mirrors (M1-M2) was used in the laser experiments. The cavity was first optimized for CW operation, generating 400 mW of output power

with 1W of incident pump power, using a 3% output coupler. Then, for initiating and sustaining mode-locked operation, the broadband SESAM/SBR was inserted into the cavity, at a second focus that was generated by M3 (ROC = 150 mm). For soliton pulse-shaping, dispersion compensation was employed with custom-designed DCMs with a GVD of  $\sim -80 \text{ fs}^2$  per bounce. The total cavity dispersion was estimated to be  $-750 \text{ fs}^2$ . A specially-designed quartz birefringent plate was used to tune the central wavelength of the pulse spectrum.

The broadband SESAM/SBR that was used in this study contained 7 pairs of  $\text{Al}_{0.19}\text{Ga}_{0.81}\text{As}/\text{Al}_x\text{O}_y$  as the Bragg stack, and a 6 nm thick strained  $\text{In}_{0.14}\text{Ga}_{0.86}\text{As}$  quantum well (sandwiched between  $\text{Al}_{0.19}\text{Ga}_{0.81}\text{As}$  barriers) as the absorber section. The SESAM/SBR was originally grown by molecular beam epitaxy with AlAs layers and  $\text{Al}_{0.19}\text{Ga}_{0.81}\text{As}$  layers as the Bragg mirror. Mesas having diameters of  $500\mu\text{m}$  were etched and the AlAs was transformed into  $\text{Al}_x\text{O}_y$  by wet thermal oxidation [6]. The use of low-index  $\text{Al}_x\text{O}_y$  material ( $n\sim 1.6$ ), in place of AlAs ( $n\sim 3$ ), in the Bragg mirror stack increased the index contrast from  $\sim 0.5$  to  $\sim 1.9$ , and enabled a reflectivity bandwidth of  $\sim 300 \text{ nm}$  centered at  $850 \text{ nm}$  [8]. Two considerations were included in the absorber design to enable broadband tuning. First, the position of the quantum well inside the standing wave electric field pattern was chosen to obtain a constant linear saturable absorption. Secondly, the quantum well thickness was chosen to remove any discontinuities in the density of states in the SESAMs/SBRs tuning range. Also, operating in the soliton regime relaxed the dependence on SESAM/SBR recovery time [7].

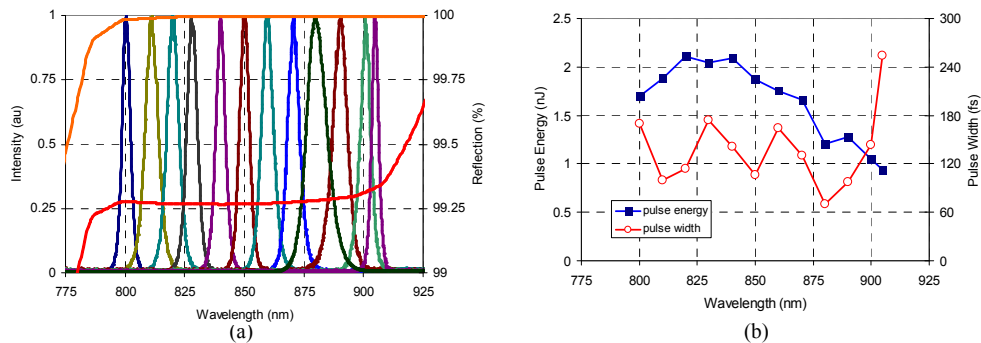


Fig. 2. (a) Sample spectra from the tunable Cr:LiSAF laser. Small signal and saturated reflectivity of the oxidized SESAM/SBR are also shown. (b) Variation of the measured pulsewidth and pulse energy of the output pulses over the demonstrated tuning range.

Fig. 2 summarizes the tuning results that were obtained with the broadband oxidized SESAM/SBR mode-locked femtosecond Cr:LiSAF laser. Mode-locking was self-starting and robust against environmental fluctuations. Continuous tuning from  $800 \text{ nm}$  to  $905 \text{ nm}$  was achieved by just adjusting the angle of the BR tuning plate. Fig. 2(a) shows sample optical spectra that were taken in  $\sim 10 \text{ nm}$  intervals within the continuous tuning range. The calculated small signal and saturated reflection of the oxidized SESAM/SBR are also shown. The laser tuning range was limited by the gain bandwidth of the Cr:LiSAF medium on the short wavelength side, and by the absorption band edge of the SEAM/SBR on the long wavelength side ( $\sim 920 \text{ nm}$ ). Fig. 2(b) shows the measured pulsewidth and pulse energy within the tuning range. The average pulse duration and pulse energies were  $\sim 140 \text{ fs}$  and  $\sim 2 \text{ nJ}$ , respectively. The repetition rate of the laser was  $85 \text{ MHz}$ , and the measured RF signal peak was  $>70 \text{ dB}$  above the background noise level. We believe the demonstrated tuning range in this study is the broadest tuning range ever reported for any SESAM/SBR mode-locked femtosecond solid-state laser. This work shows that it is possible to combine the advantages of self-starting mode-locked operation and broadband tuning using a SESAM/SBR.

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