Femtosecond tuning of Cr:colquiriite lasers with AlGaAs-based saturable Bragg reflectors

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We present a detailed experimental study of femtosecond tuning with Cr:LiSAF and Cr:LiCAF gain media using $Al_{0.95}Ga_{0.05}As/Al_{0.17}Ga_{0.83}As$-based saturable Bragg reflectors. In the experiments with Cr:LiSAF gain media, femtosecond tuning ranges of 803–831 nm (28 nm), 828–873 nm (45 nm) and 890–923 nm (33 nm) were demonstrated using three different saturable Bragg reflectors with reflectivity bands centered at around 800, 850, and 910 nm, respectively. With Cr:LiCAF gain medium, a femtosecond tuning range of 767–817 nm (50 nm) was demonstrated using the 800 nm saturable Bragg reflector. Pulses as short as 26 fs with Cr:LiSAF and 39 fs with Cr:LiCAF have been obtained, which we believe are the shortest pulses reported from Cr:colquiriite laser systems mode locked with saturable Bragg reflectors. This study further illustrates the benefits and limitations of $Al_{0.95}Ga_{0.05}As/Al_{0.17}Ga_{0.83}As$-based saturable Bragg reflectors for use in Cr:colquiriites. © 2011 Optical Society of America

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1. INTRODUCTION

Commercial mode-locked Ti:sapphire laser oscillators can provide ~100 fs long pulses, with hundreds of kilowatts of peak power and broad tunability from 680 to 1080 nm. Broad tunability in the mode-locked regime is quite important for applications such as multiphoton microscopy [1], time-resolved photoluminescence, or pump–probe spectroscopy. However, the current cost of Ti:sapphire technology is a barrier to its widespread use, limiting progress in many areas of science and technology.

Cr^{3+}:colquiriite (Cr^{3+}:LiSAF [2], Cr^{3+}:LiSGaF [3], and Cr^{3+}:LiCAF [4]) lasers are a promising low-cost alternative to Ti:sapphire due to (i) their broad emission bands covering the 750–1050 nm spectral region and (ii) the possibility of direct diode pumping with low-cost laser diodes emitting around 650 nm [5–20]. Besides enabling a significant reduction in cost, direct pumping with high-brightness diodes also greatly improves electrical-to-optical conversion efficiency. Among the Cr:colquiriites, Cr:LiSAF has the broadest gain and its demonstrated continuous-wave (cw) tuning range extends from 775 to 1042 nm [18] (extending to 1065 nm in pulsed operation [21]). Cr:LiCAF has received attention due to its blueshifted emission spectrum, which enables a cw tuning range of 754–871 nm [18] (extending to 720 nm in quasi-cw operation [4]). To date, most femtosecond laser development efforts with Cr:colquiriites have focused on fixed wavelength operation near the gain peak, which is around 800 nm for Cr:LiCAF and 850 nm for Cr:LiSAF and Cr:LiSGaF.

With Kerr-lens mode-locked (KLM) Cr:colquiriite lasers, pulses as short as ~10 fs [22–24] and femtosecond tuning ranges of 835–910 [25] and 809–910 nm [26] have been demonstrated. As an example, in the study by Robertson *et al.*, ~1 W of near diffraction-limited ($M^2 \sim 2$) pump power from two tapered laser diodes was used to pump a Cr:LiSAF laser [26]. The Cr:LiSAF laser cavity contained a prism pair for dispersion adjustment and a slit to tune the wavelength [26]. Within the tuning range (809–910 nm), the pulse widths varied between 70 and 170 fs and pulse energies were in the 0.2–1.2 nJ range [26]. Since the Kerr-lensing mechanism does not impose a bandwidth limitation, the shortest pulses and the broadest tuning range from Cr:colquiriite lasers have been obtained from KLM systems. However, the main difficulty with KLM mode-locked Cr:colquiriite lasers is the long-term stability and robustness of the mode-locked laser system, due to the relatively low nonlinear refractive index (n_2) of Cr:LiSGaF ($1.2 \times 10^{-16}\ \mathrm{cm}^2/\mathrm{W}$), Cr:LiSAF ($0.8 \times 10^{-16}\ \mathrm{cm}^2/\mathrm{W}$), and Cr:LiCAF ($0.4 \times 10^{-16}\ \mathrm{cm}^2/\mathrm{W}$, which is 8 times smaller than Ti:sapphire [18,27]). Moreover, the efficiency (average output power/pump power) of the KLM Cr:LiSAF lasers is also relatively low due to the need for critical alignment of the cavity near its stability edge.

As an alternative to KLM, femtosecond pulses can be initiated using semiconductor saturable Bragg reflectors (SBRs) [28], which are also referred to as semiconductor saturable absorber mirrors (SESAMs) [29]. Advantages of using SBRs instead of KLM include self-starting, robust mode-locked operation with long-term stability, immunity to environmental fluctuations, reduced cavity alignment sensitivity, and higher efficiencies. Using low-cost, single-mode laser diodes that emit around 650 nm (optical power of ~150 mW), and SBRs for mode-locking, turn-key femtosecond Cr:colquiriite lasers, with sub-100-fs pulses and 20–40 kW peak power were obtained with electrical-to-optical conversion efficiencies above 8% [17,19]. Once aligned, these lasers are quite stable and operate as a turn-key system for days to weeks, requiring little adjustment due to mechanical/thermal misalignments. To our knowledge, the only report of femtosecond tuning of SBR mode-locked Cr:colquiriite lasers is by Kopf *et al.*, who demonstrated a tuning range from ~825 to ~875 nm from an SBR mode-locked, multimode diode-pumped Cr:LiSAF laser [30]. However, this study used a prism pair and a slit for tuning, and for each central wavelength, the dispersion was optimized, making the cavity alignment sensitive and turn-key operation difficult.

This manuscript presents a detailed femtosecond tuning investigation of SBR mode-locked Cr:LiSAF and Cr:LiCAF lasers pumped by single-mode diodes. A quartz birefringent wave plate is used for wavelength tuning, which enables more robust operation. With the Cr:LiSAF gain medium, using an SBR centered at 850 nm (hereafter referred to as an 850 nm SBR), a femtosecond tuning range of 828–873 nm (45 nm) was obtained with average pulse widths of ~190 fs and average pulse energies of 1.87 nJ. By using an 800 nm SBR, the Cr:LiSAF laser could be tuned from 803 to 831 nm (28 nm, average pulse width of 140 fs, average pulse energy of 1 nJ). Furthermore, a 910 nm SBR resulted in a tuning range from 890 to 923 nm with the same laser. With the Cr:LiCAF gain medium, a mode-locked tuning range of 767–817 nm (50 nm), with average pulse widths of ~133 fs and average pulse energies of 1.48 nJ was obtained. To our knowledge, this study provides the first account of detailed femtosecond tuning experiments with SBR mode-locked Cr:colquiriite lasers. Furthermore, pulses as short as 26 and 39 fs were obtained with Cr:LiSAF and Cr:LiCAF lasers, respectively, which, to our knowledge, are the shortest pulses reported from SBR mode-locked Cr:colquiriite lasers.

This paper focuses on the femtosecond tuning results that were obtained with Cr:colquiriite lasers. We refer to [17–19,31] for a general description of SBR mode-locking of single-mode diode-pumped Cr:colquiriites and further discussion on *Q*-switching and multiple pulsing instabilities.

2. FEMTOSECOND TUNING OF CR:LISAF NEAR 850 NM

A. Experimental Setup

Figure 1 shows the schematic of the Cr:LiSAF laser used in the femtosecond tuning experiments near 850 nm. The Cr:LiSAF crystal was pumped by four 640 nm (Hitachi HL6385DG) linearly polarized, single-mode diodes ($M^2 < 1.05$) with circular outputs (D1–D4). The diodes have a rated output power of 150 mW with 280 mA of pump current at 25 °C. The laser diodes were cooled to 20 °C by a thermoelectric cooler and operated at 350 mA to obtain ~200 mW from each laser diode. No degradation of the pump laser diodes was observed up to hundreds of hours of operation. The diode outputs were collimated with 4.5 mm focal length aspheric lenses and combined by polarizing beam splitter (PBS) cubes. Two 65 mm focal length lenses focused the pump beams into the Cr:LiSAF crystal. The 6 mm long Cr:LiSAF crystal had a Cr concentration of 1.5% and absorbed >99% and >77% (0.9 × 85%) of the incident TM- and TE-polarized pump light at 640 nm, respectively. An astigmatically compensated, x-folded laser cavity containing two curved pump mirrors (M1–M2, radius of curvature ROC = 75 mm) was used. The cavity was first optimized for cw operation, generating 335 mW of output power with 800 mW of incident pump power (~720 mW of absorbed pump power) using a 3% output coupler. To initiate and sustain mode-locked operation, a 850 nm SBR was used. The SBR consisted of 25 pairs of $\mathrm{Al}_{0.95}\mathrm{Ga}_{0.05}\mathrm{As}/\mathrm{Al}_{0.17}\mathrm{Ga}_{0.83}\mathrm{As}$ quarter-wave layers as a Bragg mirror stack and one layer of 25 nm thick GaAs as a saturable absorber. The epitaxial growth of the SBR was performed in a solid source, multiwafer, dual-reactor molecular beam epitaxy (MBE) system (Veeco GEN 200), at typical AlGaAs growth temperatures. After the MBE growth, an additional SiO_2–TiO_2 pair was used as a high-reflection (HR) coating on the surface. The calculated modulation depth of the 850 nm centered SBR was $0.8 \pm 0.2\%$. For soliton pulse shaping, dispersion compensation was performed with custom-designed dispersion-compensating mirrors (DCMs) (M1–M5) with a group velocity dispersion (GVD) of $\sim -80\,\mathrm{fs}^2$ per bounce (800–940 nm) [32,33]. A 3 mm thick quartz birefringent plate, designed with the optic axis out of plane was used for tuning. The same 3% output coupler is also used in mode-locked tuning experiments.

B. Results

Using the 850 nm SBR, the central wavelength of the Cr:LiSAF laser could be tuned continuously from ~828 to ~873 nm (~45 nm tuning), by rotating the birefringent tuning plate. Figure 2 shows the laser pulse width and pulse energy over the tuning range. On average, the Cr:LiSAF laser generated ~188 fs pulses (assuming sech^2 pulse shape) with ~170 nm of average power at a repetition rate of 91 MHz (~1.87 nJ pulse energy). Figure 3 shows the measured spectra over the tuning range along with the estimated total cavity GVD and the calculated small-signal SBR reflectivity. The total round-trip cavity dispersion was estimated to be $\sim -900\,\mathrm{fs}^2$, where the estimate includes one bounce on the SBR, 18 bounces on the DCMs, ~3 m of intracavity air, 12 mm of Cr:LiSAF material,

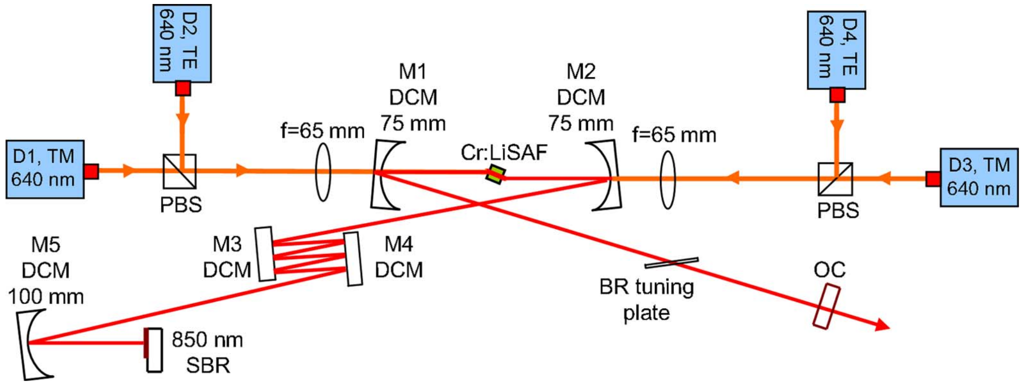

Fig. 1. (Color online) Schematic of the single-mode diode-pumped Cr:LiSAF laser used in femtosecond tuning experiments around 850 nm. The estimated total cavity dispersion is $\sim -900\,\mathrm{fs}^2$ per round trip. The total incident pump power on the crystal is ~800 mW.

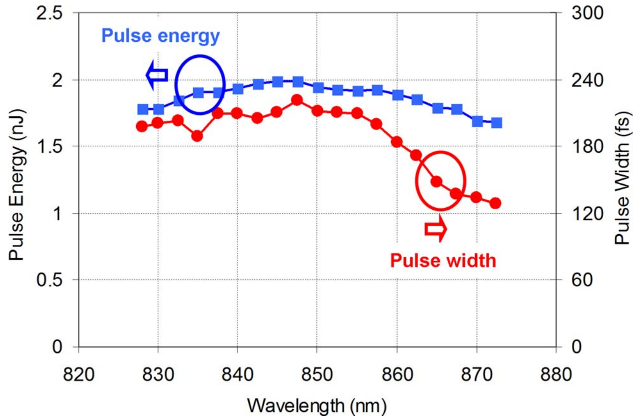

Fig. 2. (Color online) Femtosecond tuning results with the Cr:LiSAF laser using the 850 nm SBR. The total tuning range is ~45 nm (828 to 873 nm).

and 7.3 mm of quartz birefringent tuning plate. The total cavity GVD curve is relatively flat around 850 nm with a bandwidth of about 50 nm, then varies significantly due to the relatively narrow dispersion bandwidth of the SBR. We believe that the tuning range was limited by the SBR reflectivity and the dispersion bandwidth on the short wavelength side. On the long wavelength side, when the laser was configured for operation above 873 nm, the laser started to lase cw near 885 nm. This is because the absorption edge of GaAs is around 870 nm and, hence, there is insufficient modulation in the SBR to enable mode-locking above 873 nm. We anticipate that using absorber with an absorption band edge at a slightly longer wavelength (for example, an InGaAs absorber with a few percent indium, instead of pure GaAs), will increase the tuning range by 5–10 nm on the long wavelength side.

When the number of bounces on the DCM mirrors was decreased from 18 to 14, the total estimated cavity GVD decreased from ~ – 900 to –600 fs^2. At this dispersion level, continuous tunability from 835 to 870 nm (~35 nm tuning) was obtained by rotating the tuning plate. The average pulse width decreased to ~140 femtoseconds and the average pulse energy was ~1.8 nJ at a repetition rate of ~110 MHz. Compared to the previous configuration, the tuning range was narrower, since more of the SBR bandwidth was required for the shorter pulses and mode-locking stability became more susceptible to dispersion changes. The Cr:LiSAF laser can be adjusted to emit even shorter pulses; however, the tuning range is narrower. For example, [18] demonstrates a 28 nm tuning of a Cr:LiSAF laser with sub-80-fs pulses using a similar SBR centered at 850 nm (Figs. 12 and 13 in [18]).

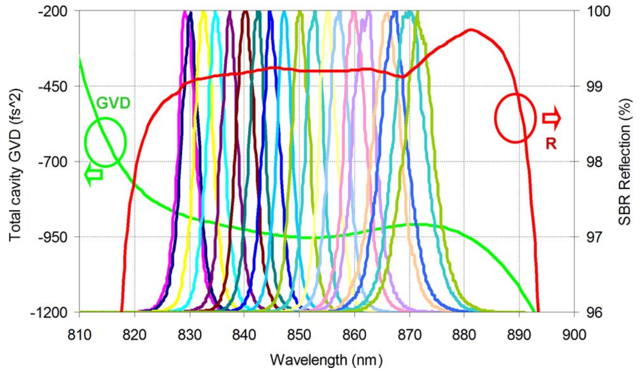

Fig. 3. (Color online) Typical spectra from the Cr:LiSAF laser, showing tunability of central wavelength from 828 to 873 nm with pulse durations of <200 fs. The data were taken with the 850 nm SBR. The calculated small-signal reflectivity of the SBR and estimated total cavity GVD are also shown.

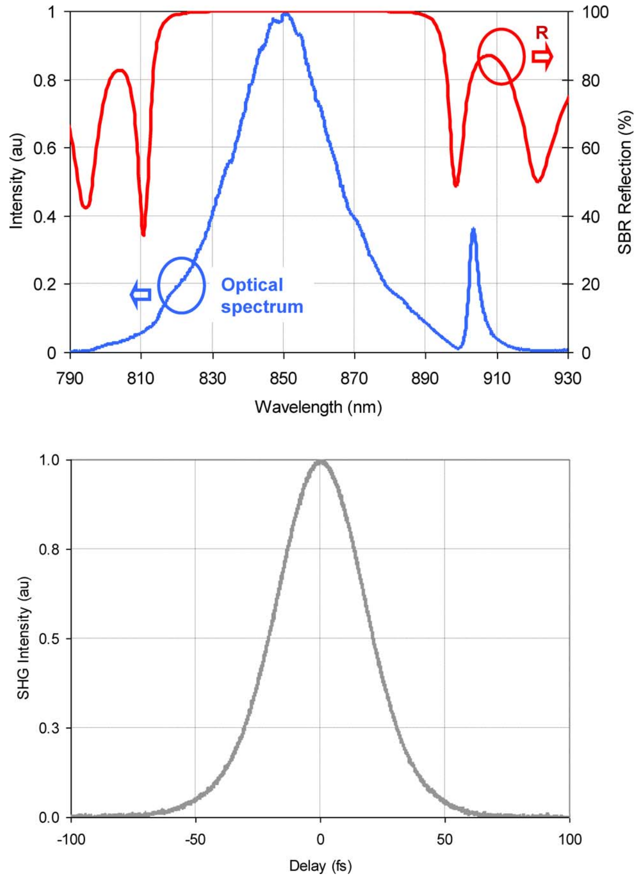

Fig. 4. (Color online) Top, optical spectrum for the 26 fs, 1 nJ pulses obtained from the Cr:LiSAF laser with the 850 nm SBR. The calculated saturated reflectivity of the SBR is also shown. Bottom, measured background-free autocorrelation trace for the 26 fs pulses.

The Cr:LiSAF laser was also configured to produce sub-30-fs pulses with the 850 nm SBR. A fused-silica prism pair with 28 cm separation was used to adjust the intracavity dispersion (for a similar cavity design, see Fig. 1 in [18]). By adjusting the prism insertion, pulses as short as 26 fs with ~1 nJ pulse energy were obtained at a repetition rate of 85 MHz. We believe these are the shortest pulses reported from SBR mode-locked Cr:colquiriite lasers. Figure 4 (top) shows the optical spectrum, centered around ~850 nm, with an FWHM of ~33 nm. The measured pulse width of ~26 fs [Fig. 4 (bottom)] was slightly larger than transform limited (23 fs), with a time–bandwidth product of ~0.36. Figure 4 (top) also shows the calculated reflectivity for the 850 nm SBR, indicating that the spectral bandwidths (or the pulse widths) are limited by the SBR bandwidth.

3. FEMTOSECOND TUNING OF CR:LISAF AROUND 800 NM

A. Experimental Setup

The experimental setup for the femtosecond tuning experiments with Cr:LiSAF around 800 nm was similar to that described in Subsection 2.A for 850 nm. The 850 nm SBR was replaced with a 800 nm SBR and the output coupler transmission was 1%. The 800 nm SBR consisted of 25 pairs of $Al_{0.95}Ga_{0.05}As/Al_{0.17}Ga_{0.83}As$ quarter-wave layers for the Bragg mirror stack and five layers of 6 nm thick GaAs quantum wells as the saturable absorber. Two pairs of SiO_2–TiO_2 layers were used as an HR coating. The calculated modulation depth of the 800 nm SBR was approximately $0.6 \pm 0.15\%$.

B. Results

Figure 5 summarizes the tuning of the femtosecond Cr:LiSAF laser around 800 nm. By rotating the tuning plate, the central wavelength was tuned from 803 to 831 nm. On average, the Cr:LiSAF laser generated ~140 fs pulses with ~90 mW of average power at a repetition rate of 83 MHz (~1 nJ pulse energy). The tuning range was limited by the SBR reflectivity and dispersion bandwidth on the long wavelength side (see Fig. 6). As the laser is tuned above 825 nm, the average output power decreases (Fig. 5) due to the increased SBR loss. Above 825 nm, the reduced output power and the higher cavity dispersion also caused an increase in pulse widths (Fig. 5).

The limitation to tuning below 803 nm is not clear and may be due to several factors. As Fig. 6 shows, the total cavity dispersion estimate is not flat below ~800 nm. First, the dispersion of the 800 nm SBR deviated from ~0 fs^2 below 775 nm and above 825 nm. Second, the dispersion bandwidth of the custom-designed DCMs was 800–940 nm, and, hence, the dispersion of the cavity was not optimized below 800 nm. By decreasing the pump power, femtosecond tuning in the 791–795 nm range was also obtained (the wavelength jumped from 795 to 803 nm). By using Gires–Tournois interferometer (GTI) mirrors for dispersion compensation and using the same SBR at 800 nm, the laser could be continuously tuned from 794 to 825 nm (with ~300 fs long pulses). This suggests that the jump in tuning is due to the DCM mirrors. Also, cw tuning experiments showed that Cr:LiSAF can lase down to 775 nm. Hence, with a different DCM design, a broader continuous tuning range should be possible around 800 nm.

Finally, using the 800 nm SBR, pulses as short as 41 fs could be obtained from the Cr:LiSAF laser with a fused-silica prism pair for fine dispersion tuning. This result has been described in an earlier publication (Fig. 6 in [18]).

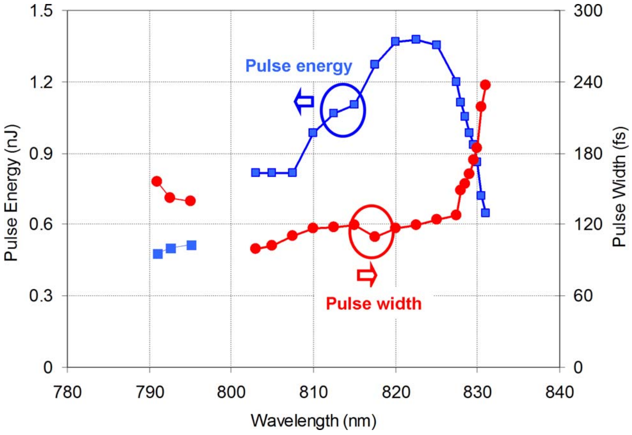

Fig. 5. (Color online) Femtosecond tuning results for the Cr:LiSAF laser with the 800 nm SBR. The total tuning range is ~28 nm (803 to 831 nm). At a reduced pump power level, the laser also tuned from 791 to 795 nm.

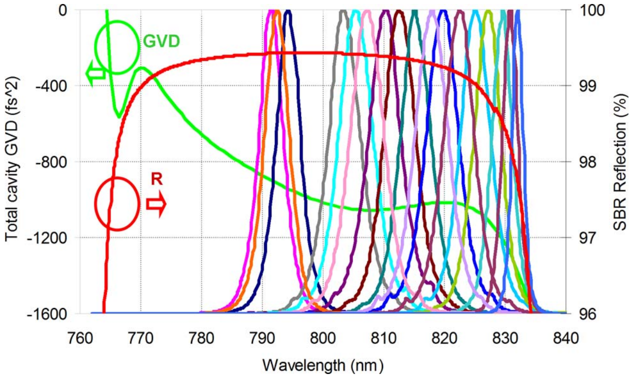

Fig. 6. (Color online) Typical spectra from the Cr:LiSAF laser showing tunability of central wavelength from 803 to 831 nm for ~140 fs pulses. The data were taken with the 800 nm SBR. Calculated small-signal reflectivity of the SBR and estimated total cavity GVD are also shown.

4. FEMTOSECOND TUNING OF THE CR: LISAF LASER AROUND 910 NM

The experimental setup for the femtosecond tuning experiments with the Cr:LiSAF laser around 900 nm was also similar to that described for 800 and 850 nm operation. The 910 nm SBR consisted of 25 pairs of $Al_{0.95}Ga_{0.05}As/Al_{0.17}Ga_{0.83}As$ quarter-wave layers for the Bragg mirror stack and a 15 nm thick $In_{0.10}Ga_{0.90}As$ quantum well as the saturable absorber. The calculated modulation depth of the 910 nm SBR was $1.2 \pm 0.3\%$. With the 910 nm SBR, broad continuous femtosecond tuning could not be achieved. When the tuning plate was rotated, continuous tuning was generally obtained only over a 10–15 nm range. Tuning at other wavelengths required adjustment of the focus onto the SBR and cavity dispersion (by changing the number of bounces on DCM mirrors). We believe that this behavior might be caused by dispersion from water absorption lines in air around these wavelengths. Figure 7 summarizes the tuning results around 900 nm, while Fig. 8 shows the output spectra. We stress that, unlike the previous results, the laser was realigned in order to obtain the data shown in Figs. 7 and 8. To cover the full range, not only was the tuning plate rotated, but the SBR position was changed (to adjust the focus on the SBR) and/or the amount of cavity dispersion was changed. The tuning range covers 890 to 922 nm. The average output power was >100 mW

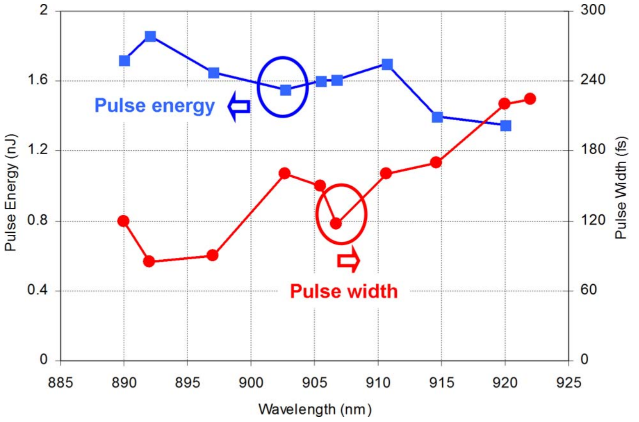

Fig. 7. (Color online) Femtosecond tuning results for the Cr:LiSAF laser using the 910 nm SBR. The total tuning range is ~32 nm (890 to 922 nm). Obtaining the whole tuning range required adjustment of the focus on the SBR and/or the cavity dispersion level.

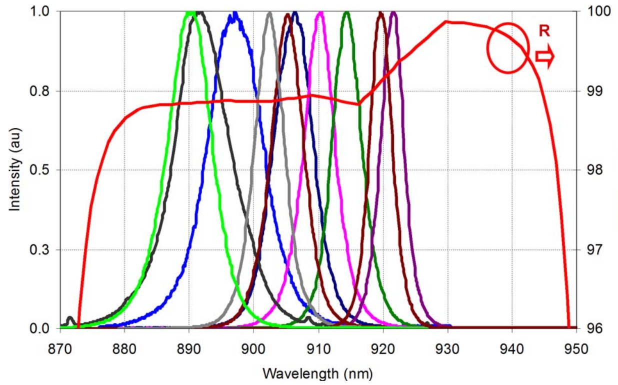

Fig. 8. (Color online) Sample spectra from the Cr:LiSAF laser, showing tunability of central wavelength from 890 to 922 nm. Tuning over the whole range required additional adjustment of the focus on the SBR and/or the cavity dispersion level. The data were taken with the 910 nm SBR. Calculated small-signal reflectivity of the SBR is also shown.

(>1.2 nJ pulse energy) and the pulse width varied between 75 and 300 fs. We believe that tuning below 890 nm is limited by the dispersion and reflectivity bandwidth of the SBR, while tuning above 922 nm is limited by the absorption edge of the bulk absorber in the SBR (around ~920 nm). A broader and continuous femtosecond tuning range around 900 nm might be achievable using an SBR with a lower modulation depth (and a lower tendency for *Q*-switched mode locking [34]), since the 1.2% modulation depth of the 910 nm SBR is more than required to initiate/sustain cw mode-locked operation for Cr:LiSAF. Moreover, a quantum-well absorber design, rather than the bulk absorber used in this study, and a different band-edge position should improve the femtosecond tuning results.

5. FEMTOSECOND TUNING OF CR:LICAF AROUND 800 NM

A. Experimental Setup

Figure 9 shows the schematic for the Cr:LiCAF laser used for femtosecond tuning around 800 nm. The pump geometry is the same as previously described for the Cr:LiSAF laser. A 2.5 mm long, 11% chromium-doped Cr:LiCAF crystal was used as the gain medium; it absorbed >700 mW of the incident pump power (~800 mW). The 800 nm SBR was used to initiate and sustain mode locking. The output coupler had a transmission of about 2% around 800 nm. Commercially available pump mirrors, DCM mirrors, and GTI mirrors (Layertec, inc.) were used. In Fig. 9, mirrors M1–M3 are standard pump mirrors with low dispersion over the 750–850 nm wavelength range. Dispersion compensation is accomplished using the GTI and DCM mirrors. High-dispersion GTI mirrors were used because too many bounces on DCM mirrors would be required to cancel dispersion from the Cr:LiCAF crystal (length ~ 5 mm, GVD ~ 125 fs^2), the quartz birefringent tuning plate (length ~ 7.3 mm, GVD ~ 260 fs^2), and air (length~ 3.5 m, GVD ~ 70 fs^2). The DCM mirrors had a GVD of only ~$45 \pm 10\,\mathrm{fs}^2$ per bounce (750–920 nm), whereas the GTI mirrors had ~ $-550 \pm 50\,\mathrm{fs}^2$ of GVD per bounce. However, the dispersion bandwidth of the GTI mirrors was narrow (790–815 nm), and dispersion oscillated strongly outside this range. In femtosecond tuning experiments, a flat dispersion profile is desired to obtain optimal tuning. Hence, using GTI mirrors limits the tunability range.

B. Results

Figure 10 summarizes the Cr:LiCAF tuning results, showing the measured pulse widths and pulse energies within the tuning range. The laser was continuously tunable from 785 to 817 nm (~32 nm) by rotating the birefringent tuning plate. Figure 11 shows the output spectra along with the estimated total cavity dispersion and SBR reflectivity bandwidth. Tuning was limited by the dispersion bandwidth of the GTI mirror on the short wavelength side. The average pulse duration was 133 fs and the average pulse energy was 1.48 nJ. The laser repetition rate was 86 MHz. The 800 nm SBR reflectivity spectra in Fig. 11 is shifted to shorter wavelengths compared to Fig. 6, which is a different SBR sample where the reflectivity shift is a result of variations in growth conditions (same SBR design but different MBE growth). Except for this small reflectivity shift, there was no significant variation in the SBR parameters. In the tuning studies with Cr:LiCAF, the 800 nm SBR with a reflectivity shifted toward shorter wavelengths was used, since obtaining shorter wavelength tuning is important for applications such as multiphoton microscopy or amplifier seeding.

To confirm that the GTI mirror dispersion bandwidth limited tuning below 785 nm, the cavity dispersion was made more negative by increasing the number of GTI mirror bounces. Using two bounces on the GTI mirror, tuning in the 775–785 nm region (12–150 fs, 1.6 nJ pulses), and with three bounces on the GTI mirror, tuning in the 765–775 nm region (170 fs, 1.37 nJ pulse at 767 nm) could be obtained. Figure 12 shows the mode-locked spectra together with the reflectivity of the 800 nm SBR. Tuning above 817 nm is limited by the SBR bandwidth, which was also apparent from a decrease in output power (Fig. 9). The total tuning range extends

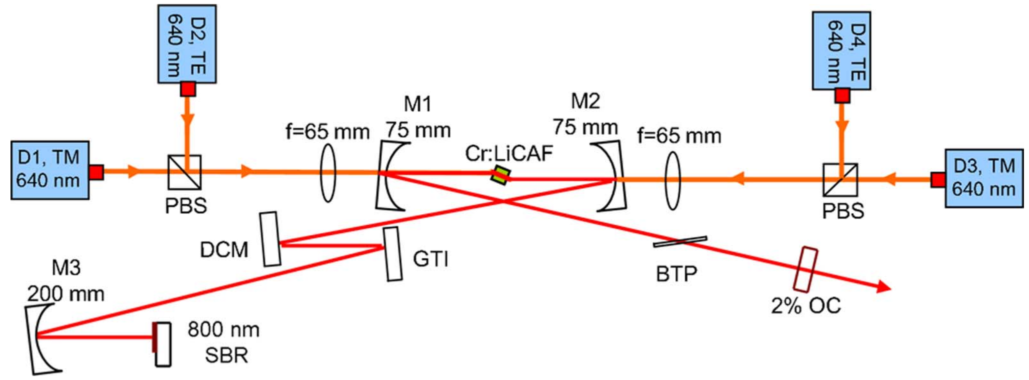

Fig. 9. (Color online) Schematic of the single-mode diode-pumped Cr:LiCAF laser used in femtosecond tuning experiments around 800 nm.

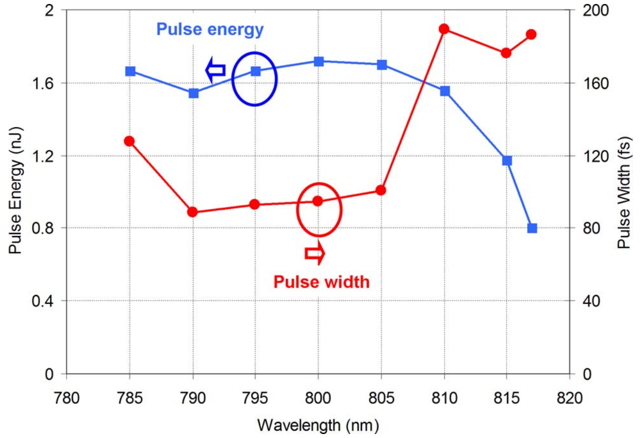

Fig. 10. (Color online) Femtosecond tuning results for the Cr:LiCAF laser using the 800 nm SBR. The laser was continuously tunable from 785 to 817 nm (32 nm bandwidth).

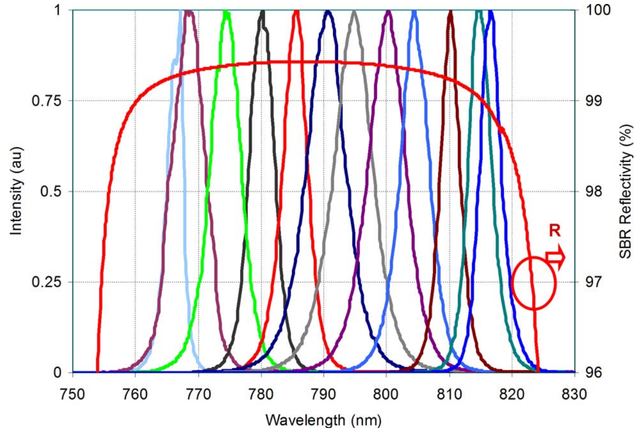

Fig. 12. (Color online) Full tuning range obtained with the Cr:LiCAF laser using the 800 nm SBR. The calculated reflectivity of the SBR is also shown. The total tuning range extends from 767 to 817 nm (50 nm bandwidth).

from 767 to 817 nm (50 nm), but multiple dispersion settings were required to cover this wavelength range. However, this suggests that, with a different DCM mirror having flat dispersion, it should be possible to obtain continuous tuning.

Last, we have generated ultrashort pulses with a Cr:LiCAF laser using DCM mirrors. By using four bounces (eight per round trip) on the DCM mirrors, a total cavity GVD of about −100 fs^2 around 800 nm could be obtained in one round trip. In this configuration, the laser produced ~39 fs pulses with 125 mW of average output power at a repetition rate of 77 MHz, with an absorbed pump power of ~700 mW. The corresponding pulse energy was 1.62 nJ. Figure 13 (top) shows the optical spectrum as well as the estimated cavity dispersion. Figure 13 (bottom) shows the measured pulse autocorrelation. The optical spectrum was centered around ~805 nm and had a bandwidth of 18.8 nm, broad enough to support ~36 fs pulses. The dispersion of the cavity was around −100 fs^2 at the center of the optical spectrum, and deviates at the extremes due to the relatively narrow dispersion bandwidth of the SBR. Figure 13 shows that the optical spectrum covers a significant portion of the SBR bandwidth. Based on results from the Cr:LiSAF laser, the SBR should have enough bandwidth to obtain pulses as short as −25 fs^2. Hence, we have also tried to obtain even shorter pulses with a Cr:LiCAF laser from a cavity including a prism pair for fine dispersion tuning. However, *Q*-switched mode-locking, multiple-pulsing, and cw-breakthrough instabilities prevented us from obtaining stable cw-mode-locked operation with shorter pulses. We believe that this is due to the lower emission cross section of the Cr:LiCAF gain media [19], which results in a very narrow SBR mode-locking ranges for sub-50-fs pulses [35].

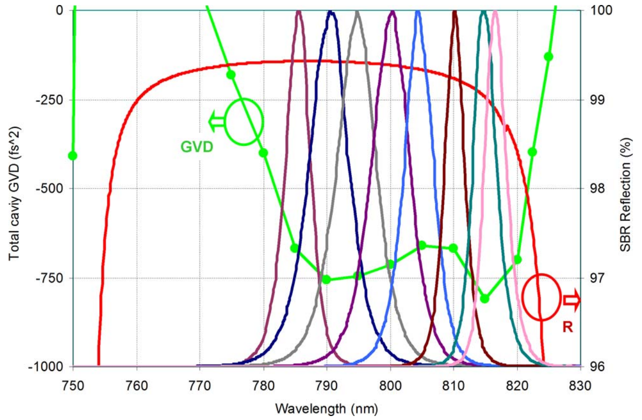

Fig. 11. (Color online) Typical spectra from the mode-locked Cr:LiCAF laser, showing tunability of the center wavelength from 785 to 817 nm. The data were taken with the 800 nm SBR. Calculated small-signal reflectivity of the SBR and estimated total cavity GVD are also shown.

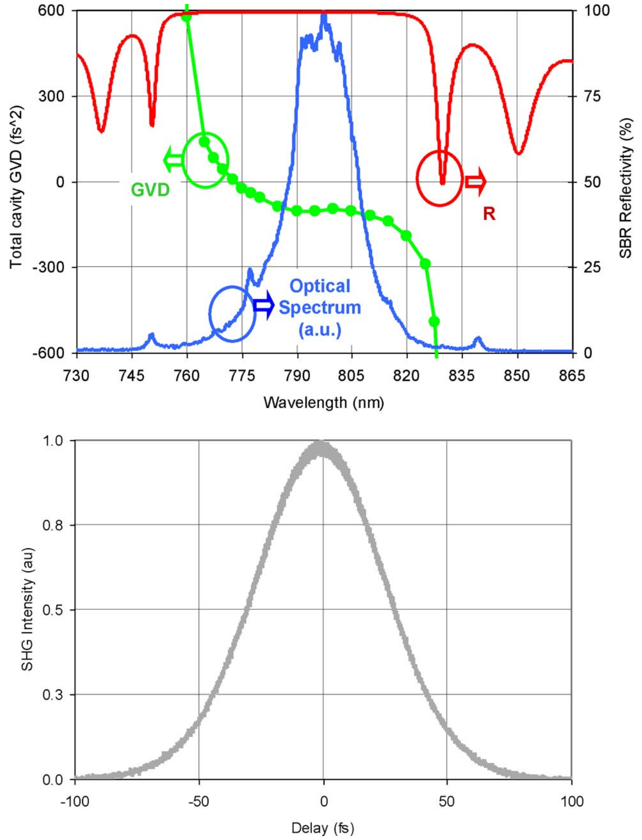

Fig. 13. (Color online) Top, optical spectrum of the ~39 fs, 1.62 nJ pulses and the calculated reflectivity curve for the 800 nm SBR and estimated total cavity dispersion. Bottom, measured background-free autocorrelation trace shows pulse durations of 39 fs.

6. SUMMARY AND DISCUSSION

This manuscript presents a comprehensive study of femtosecond tuning of Cr:colquiriite lasers pumped by single-mode diodes. In each cavity configuration, two different regimes of tunable mode-locked operation were demonstrated: (1) broad, continuous femtosecond tuning at higher negative intracavity dispersion and (2) sub-50-fs pulse generation spanning the spectral bandwidth of the SBR at intracavity dispersions closer to zero. A quartz birefringent plate was used for tuning, which was easier and more robust compared to tuning with a prism pair and a slit. With the Cr:LiSAF gain media, and an 850 nm SBR, a femtosecond tuning range of 828–873 nm (45 nm) was obtained with average pulse widths of ~190 fs and average pulse energies of 1.87 nJ. In addition, a femtosecond tuning range of 835–870 nm (35 nm) was obtained with average pulse widths of ~140 fs and average pulse energies of 1.8 nJ. In both cases, tuning was performed by rotating the birefringent plate. With the 800 nm SBR, femtosecond tuning of the Cr:LiSAF laser was obtained in the 803–831 nm range (28 nm) with average pulse widths of ~140 fs and average pulse energies of 1 nJ. We also demonstrated femtosecond tuning of a Cr:LiSAF laser in the 890–923 nm region, using a 910 nm SBR. However, both the cavity dispersion and the spot size on the SBR required adjustment to obtain this tuning range. With Cr:LiSAF, the shortest pulse widths obtained using the 800, 850 and 910 nm centered SBRs were 41, 26, and 75 fs, respectively.

Using a Cr:LiCAF gain medium, a mode-locked tuning range of 767–817 nm (50 nm), with average pulse widths of ~133 fs and average pulse energies of 1.48 nJ was obtained. The laser could be tuned by rotating the birefringent plate in the 785–817 nm region, but required dispersion adjustment to tune below 785 nm. We believe that, with a different DCM mirror design, the entire tuning range can be continuously covered. Pulses as short as ~39 fs were obtained, which we believe are the shortest pulses from SBR mode-locked Cr:LiCAF lasers.

The total femtosecond tuning range that was demonstrated in this study extends from 767 to 923 nm. The total cw tuning range that was demonstrated by Cr:colquiriites covers the 754–1042 nm region. We envision that it should be possible to cover this full cw tuning range with improved SBRs and DCMs.

Because of the limited reflectivity and dispersion bandwidth, the broadest obtainable tuning range using a single SBR is about 50 nm using AlGaAs-based SBRs. The bandwidth of the SBR also limited the pulse widths; however, ~26 fs pulses were still obtained. In the future, the use of oxidized broadband SBR mirrors [36] may enable the generation of pulses as short as 10 fs [13,22], or broadly tunable sub-100-fs pulses from ~800 to ~1000 nm. Also, the peak power that was obtained in this study was in the 20–40 kW range and was limited by the available pump power (~800 mW). However, earlier studies have shown that the peak power can be scaled up to the ~100 kW level by multipass cavity Cr:colquiriite lasers at an ~10 MHz repetition rate [37], or to the ~1 MW level by cavity-dumped Cr:colquiriite lasers with pulse repetition rates of up to 50 kHz [38]. Moreover, improvements in pump diode output power are expected to enable peak power scaling. For example, recently, a 1 W, nearly transform-limited ($M^2 \sim 1.3$) 650 nm diode laser has been demonstrated (which is approximately 5 times brighter than the pump laser diodes that were used in this study) [39]. We believe that tunable femtosecond Cr:colquiriite lasers have the potential to become a versatile, low-cost femtosecond source for several important application areas in science and engineering, including multiphoton microscopy [1,40].

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