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Compact and efficient Cr:LiSAF lasers pumped by one single-spatial-mode diode: a minimal cost approach

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In this study, we report a minimal-cost and minimal-complexity Cr:LiSAF laser that is pumped only by one inexpensive single-spatial-mode diode. The pump diode, which was originally developed for DVD-writers, provides 130 mW of output power at 660 nm with an efficiency of 30%. This simple pump source enables the construction of a Cr:LiSAF laser that (i) has an estimated total material cost below US$ 5k, (ii) has a footprint of about 20 × 30 cm, (iii) does not require active cooling, and (iv) can be driven by batteries. All of these make this system ideal for applications that require portability. In continuous-wave (cw) laser experiments, we have demonstrated lasing thresholds as low as 2 mW, slope efficiencies as high as 52%, and output powers up to 58 mW. A record cw tuning range extending from 780 to 1110 nm has also been obtained. In cw mode-locking experiments using a saturable Bragg reflector at 850 nm, the Cr:LiSAF laser produced 100 fs pulses with an average power of 38 mW at a repetition rate of 235 MHz. Using a more compact laser cavity, we have also obtained 130 fs pulses with an average power of 33 mW at a repetition rate of 757 MHz. The corresponding electrical-to-optical conversion efficiencies in cw and cw mode-locked regimes were 12.8% and 8.4%, respectively. These results show that, with the progress in laser-diode and optical mirror technology in the last decade, reasonable output powers can now be obtained from Cr:LiSAF lasers that are pumped only by one single-spatial-mode diode. We believe that this compact, low-cost, and simplistic Cr:LiSAF laser system may be an attractive source for several applications including amplifier seeding.

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1. INTRODUCTION

Broadly tunable continuous-wave (cw) and mode-locked laser sources are attractive for many scientific and technological applications, especially for those that benefit from flexibility in wavelength [1,2]. If these tunable sources can also be directly diode pumped, most of the time this provides additional advantages such as lower cost, higher electrical-to-optical conversion efficiency, compactness (lower weight and volume), lower noise, and reduced cooling requirements [3–11]. Hence, there is a great motivation to develop directly diode pumped cw and femtosecond laser sources with broad tuning range.

Among the diode-pumped solid-state laser media, the Ti:sapphire has the broadest gain bandwidth that supports pulses as short as 5 fs, as well as tunability from 680 to 1180 nm [12–16]. However, Ti:sapphire crystals exhibit rather high passive losses together with a relatively low product of fluorescence lifetime and emission cross section ($130\ \mu s \times 10^{-20}\ cm^2$) [7,15]. These parameters result in relatively high lasing thresholds [13,15]. For example, upon pumping Ti:sapphire with a single 1 W GaN diode at 450 nm ($M^2 \sim 1.5$), only 13 mW of average power and a pulsewidth of 114 fs have been obtained in cw mode-locked operation (lasing threshold with a 0.5% output coupler (OC) was 106 mW in cw regime) [15,16]. This recent study also showed that there are additional parasitic losses in Ti:sapphire when it is excited at such short wavelengths [15,16]. Hence, until better pump diodes at longer wavelengths around 500 nm become available, high-power frequency-doubled neodymium lasers will remain the most suitable source for pumping Ti:sapphire lasers. Unfortunately, this conventional approach is relatively expensive and electrically inefficient, which limits the widespread adoption of Ti:sapphire technology.

Nd and Yb-based systems are also attractive gain media for the development of diode-pumped low-cost cw and fs laser and amplifier systems due to the existence of low-cost InGaAs diodes around 975 nm [9,10,17,18]. For example, state-of-the-art Yb-doped systems could provide down to 35 fs pulses [19], with optical-to-optical conversion efficiencies above 50% [5], and average powers above 100 W [11,20]. Their long upper state lifetimes also enable efficient energy storage that makes them suitable especially as an amplifier media [18,21–23]. However, due to their relatively narrow gain bandwidths, the obtainable pulse widths from these systems are limited to about the 50 fs level, and more importantly, their tuning range is relatively narrow (~100 nm). Hence, these systems are not very suitable substitutes for Ti:sapphire for many applications.

As an attractive alternative to Ti:sapphire, Cr:LiSAF also possesses a broad gain bandwidth around 800 nm, providing total tunability from 780 to 1110 nm and enabling generation of pulses on a 10 fs level [7,24,25]. Furthermore, Cr:LiSAF crystals can have very low passive losses, and the product of their fluorescence lifetime and emission cross sections is relatively high ($320\ \mu s \times 10^{-20}\ cm^2$) [7,24]. Hence, the lasing threshold in Cr:LiSAF lasers can be quite low. Moreover, Cr:LiSAF has an intrinsic slope efficiency of 54% [24], enabling the construction of highly efficient systems. Lastly, Cr:LiSAF has broad and relatively strong absorption bands around 650 nm, allowing for direct excitation by low-cost red laser diodes.

Various diode types have been used to pump Cr:LiSAF lasers to date, including single-spatial-mode laser diodes (also known as single-transverse-mode diodes or ridge waveguide lasers) [3,4,8,26–30], broad-stripe single-emitter diodes [31,32], tapered diodes [33], and laser diode arrays [34]. Broad-stripe single-emitter diodes, tapered diodes, and laser diode arrays provide higher pump powers (1 to 10 s of Watts) for pumping Cr:LiSAF lasers. However, compared to single-spatial-mode laser diodes, these diodes (i) are more expensive, (ii) have reduced output beam quality, (iii) require active cooling, and (iv) need more expensive, bulky, and complex diode drivers. In short, these high-power diodes sometimes enable power scaling of Cr:LiSAF lasers but at the expense of increased cost and complexity. As an alternative pump source, single-transverse-mode laser diodes are low-cost (US~100), have diffraction-limited beam quality, and can be driven by inexpensive (US~100) drivers. Moreover, some of the state-of-the-art single-spatial-mode laser diodes around 650 nm (such as HL6545MG) do not require active cooling. This fact enables construction of minimal cost and portable cw and femtosecond laser systems with reasonable output power levels.

Single-spatial-mode laser diodes have been first used as pump sources for Cr:LiSAF by Scheps *et al.* as early as 1991 [26]. In those years, the commercial red diodes provided only 10 mW of pump power, which was barely enough to reach lasing thresholds in cw Cr:LiSAF lasers (nowadays lasing thresholds are lower due to the improvements in crystal and mirror quality) [26]. In 1999, using a 30 mW laser diode, Valentine *et al.* demonstrated 200 fs pulses with 0.23 mW of average power in cw mode-locked operation [4]. Later, in 2002, the output power levels from single-spatial-mode laser diodes reached the 50–60 mW level, which enabled power scaling of femtosecond Cr:LiSAF lasers to the 45 mW level [28,29,35–37]. Recently, using state-of-the-art single-spatial-mode red laser diodes with 130–200 mW power, output levels of fs Cr:LiSAF lasers have been scaled to the 150 mW level [8,38]. However, for power scaling, most of the reported Cr:LiSAF lasers in the literature used two to six single-spatial-mode laser diodes as pump sources via polarization multiplexing, wavelength multiplexing, and/or double end-pumping (also see Table 1 in Section 4). However, these approaches increase cost and complexity of the laser systems. Moreover, the complexity in pump optics makes these systems quite susceptible to alignment problems, reducing long-term stability and limiting commercialization opportunities.

In this work, we have investigated a minimal-cost and minimal-complexity Cr:LiSAF laser that is pumped only by one state-of-the-art single-spatial-mode diode (SMD). The highly reliable pump diode is used commercially in DVD-writers and provides 130 mW of diffraction-limited pump power around 660 nm. The pumping system (diode, diode driver, diode holder, and collimating optics) has a total cost of about $500 and can be driven with 8 AA-type batteries for 7 to 10 h. This inexpensive pumping also enables the construction of a Cr:LiSAF laser with an estimated material cost below $5 000. Moreover, the entire laser system has a footprint of only 20×30 cm, does not require active cooling, and can be driven by batteries, making the system ideal for applications that require portability. In cw laser experiments with the Cr:LiSAF laser, we have demonstrated an extremely low lasing threshold of 2 mW, slope efficiencies as high as 52%, and output powers up to 58 mW. A record cw tuning range extending from 780 to 1110 nm has also been obtained. To the best of our knowledge, this result represents the first demonstration of cw tuning above 1042 nm for Cr:LiSAF. In cw mode-locking experiments, using a 0.5% OC, 100 fs pulses with an average power of 38 mW, and with an optical spectrum centered at 865 nm, have been obtained at a repetition rate of 235 MHz. With a more compact cavity and using a 0.1% OC, 130 fs pulses with an average power of 33 mW have also been demonstrated at a repetition rate of 757 MHz. These results show that, with the progress in laser diode technology in the last decade and with the improvements in laser mirror technology, we can now obtain 30–40 mW of average powers from fs Cr:LiSAF lasers that are pumped by just one SMD. On the contrary, reaching this power level required four diodes a decade ago. This simplification in pumping Cr:LiSAF lasers enables reduction of cost and complexity as well as development of more robust systems due to simplified requirements in pump alignment. We believe that this compact, low-cost, and efficient Cr:LiSAF laser system might be an attractive source for applications such as amplifier seeding [39,40] that do not require high levels of average output power.

The paper is organized as follows: Section 2 describes the experimental setup. In Sections 3 and 4, we present the cw and cw mode-locked lasing results, respectively. Finally, in Section 5, we summarize the results and provide a general discussion.

2. EXPERIMENTAL SETUP

Figure 1 shows a schematic of the Cr:LiSAF laser cavity. One linearly polarized, 660 nm, AlGaInP multiquantum well SMD with a diffraction-limited beam profile was used as the pump source (HL6545MG, Hitachi). The pump diode provided up to 130 mW of out power at a drive current of 180 mA (2.5 V),

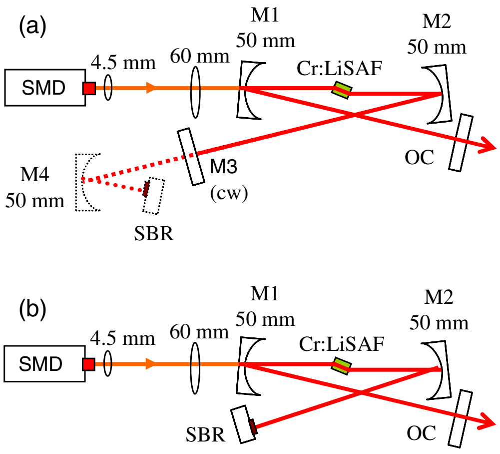

Fig. 1. (Color online) Schematic of the one SMD-pumped Cr:LiSAF laser. (a) Cavity that is used in cw experiments as well as in mode-locking experiments with repetition rates up to 500 MHz (dashed lines indicate the mode-locked laser cavity). (b) Cavity that is used in mode-locking experiments at the repetition rate of 750 MHz. SBR: Saturable Bragg reflector.

corresponding to an electrical-to-optical conversion efficiency of 30% (450 mW electrical consumption). The diode was driven by a low-cost driver board (LD1255, Thorlabs, US~100), which can be powered for 7–10 h using eight AA type batteries. The bare diode output had an asymmetric beam profile with an aspect ratio of approximately 2 ($\theta_\perp \approx 17°$, $\theta_\parallel \approx 10°$). Therefore, a built-in cylindrical microlens was used to obtain a circular beam profile. The diode with the built-in microlens is commercially available at a cost of $150 (VPSL-0660-130-X-5-G, Blue Sky Research). The diode was mounted without any active cooling using a commercial collimating tube package, which uses a 4.5 mm focal length aspheric lens with an NA of 0.55 (LT230P-B, Thorlabs). A lens of a focal length of 60 mm focused the collimated pump beam into the Cr:LiSAF crystal. The spot size inside the Cr:LiSAF crystal can be adjusted by translating the 4.5 mm focal length collimating lens within its housing. We note here that there are other SMDs available with even higher output powers, such as HL6385DG (642 nm, 170 mW) and HL63133DG (637 nm, 170 mW). Despite this fact, in our study we have chosen to use HL6545MG (660 nm, 130 mW) due to its superior thermal specifications. For example, cooling the HL6545MG diode to 5 °C only increases the output powers from about 130 to 138 mW; hence, cooling of the diode is not really necessary. Since the Cr:LiSAF crystal does not also require active cooling at these pump power levels, this greatly reduces the complexity of the system, saves on cooling costs, and enables the construction of a portable system. On the other hand, active cooling was necessary in other higher power SMDs (HL6385 DG and HL63133DG). In this way, one can improve the output power levels we are reporting in this study by using higher power diodes but at the expense of increased complexity and cost.

An astigmatically compensated, x-folded laser cavity was employed in the cw laser experiments [solid lines in Fig. 1(a); dashed lines indicate the mode-locked laser cavity]. The resonator had two curved pump mirrors (M1 and M2, $R = 50$ mm), a flat end mirror (M3), and a flat OC. All the mirrors in the cavity except the OC (M1–M4) had high reflectivity extending from about 840 to 1100 nm and had >95% transmission in the wavelength range of the pump (set 1 in Fig. 4 below). In the experiments, we have used more than 10 different OCs with transmissions ranging from 0.015% to 5%. Some of these specimens were broadband, and some were relatively narrow with a bandwidth of about 100 nm centered around 800 or 1000 nm. Arm lengths of 20 cm (OC arm) and 30 cm were implemented to obtain a laser mode size of $\sim$15–20 μm inside the Cr:LiSAF crystal. The gain medium was a 7 mm-long, Brewster-cut, 1.5% Cr-doped Cr:LiSAF crystal mounted with indium foil in a copper holder. At the maximum driving current (180 mA), 125 mw of pump power was incident on the crystal. The crystal absorbed about 99.5% of the incident TM polarized pump light at 660 nm. In the cw tuning experiments, a quartz birefringent filter was used to tune the laser wavelength. To cover the full tuning range of Cr:LiSAF (below 850 nm, which is not covered with the main set 1 mentioned above), other pump mirrors were also applied (set 2 in Fig. 4 below). This set had reflectivity greater than 99.8% from 750 to 850 nm and >95% transmission at the pump wavelength.

For mode-locking experiments, a saturable Bragg reflector (SBR) [41] was inserted into the cavity, to initiate and sustain mode-locked operation [also referred to as semiconductor saturable absorber mirror (SESAM [42])]. The SBR had a central reflectivity around 850 nm and an estimated modulation depth of (0.8 ± 0.2)% (see Fig. 5(b) in [33]). In the mode-locking experiments, the cavity in Fig. 1(a) was used for pulse repetition rates ranging from 250 to 500 MHz, where as the cavity in Fig. 1(b) was preferred for the experiments at 750 MHz repetition rate. A 50 mm radius of curvature mirror (M4) was used to focus the intracavity beam on the SESAM in lower repetition rate cavities. Mirrors M1–M4 with group velocity dispersion of ~ -60 to -80 fs^2 per bounce provided the required negative dispersion. The estimated total round-trip cavity dispersion was ~ -200 fs^2 and ~ -50 fs^2 for the cavities in Fig 1(a) and 1(b), respectively. The SBR mode-locked laser was self-starting (except for the 750 MHz cavity, which required shaking of the SBR), immune to environmental fluctuations, and did not require careful cavity alignment, enabling turnkey operation.

3. CW OPERATION

A. CW Efficiency and Findlay–Clay Analysis

This section presents cw lasing results for the one SMD-pumped Cr:LiSAF laser. Slope efficiency was measured using seven OCs with transmissions ranging from 0.1% to 5%. All the data in this paper were taken without any active cooling of the gain medium. Measured cw laser efficiencies of Cr:LiSAF at representative levels of output coupling are depicted in Fig. 2. Almost identical results were obtained using 0.1 to 1% OCs. Due to the increase in lasing thresholds, power levels decreased for OCs with transmissions above 1% (Fig. 3). An output power as high as 58 mW was obtained at an absorbed pump power of 125 mW with Cr:LiSAF using the 1% OC. The corresponding lasing threshold and the slope efficiency were 11.2 mW and 52%, respectively. Using a high reflector as the OC, we have measured record low lasing thresholds of 2 mW. This value is also identical to what is recently achieved with SMD-pumped Nd:glass lasers, which are known to have low lasing thresholds due to the narrow and strong emission lines [17]. Moreover, to our knowledge, this is the lowest lasing threshold obtained from any transition-metal-doped solid-state gain medium to date. Our estimate of the total cavity losses per round trip of approximately (0.3 ± 0.1)% is based on measuring the lasing threshold with different OCs (Fig. 3, Findlay—Clay analysis [43,44]). This corresponds to a maximum loss level of 0.2% per cm for the Cr:LiSAF crystal, which

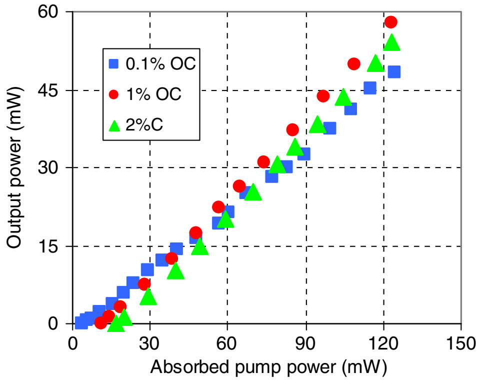

Fig. 2. (Color online) CW output power versus absorbed pump power for the one SMD-pumped Cr:LiSAF laser taken at 0.1%, 1%, and 2% output coupling.

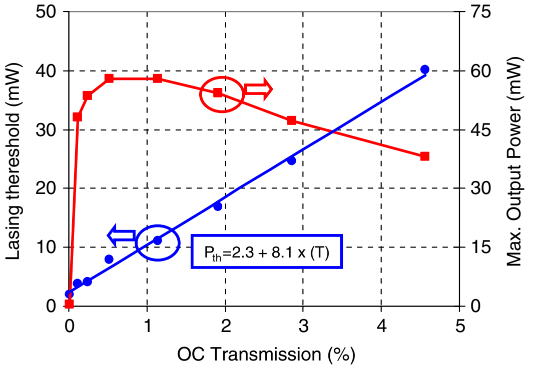

Fig. 3. (Color online) Left axis: measured variation of the pump power required to attain lasing (P_{th}) as a function of OC transmission T. Solid-line is the best linear fit to the experimentally measured data. Using Findlay—Clay analysis, the round-trip passive cavity loss L was estimated to be $(0.3 \pm 0.1)\%$. Right axis: variation of cw output power of Cr:LiSAF laser with output coupling, at ~125 mW of absorbed pump power.

is a major advantage compared to other crystals such as Ti:sapphire (approximately 2% loss per cm is reported in Ti:sapphire, depending on the doping) [15]. The slope efficiency of our Cr:LiSAF laser (52%) comes close to the reported intrinsic value from the literature (54% in [24], 53% in [8]). This fact highlights efficient mode-matching between the pump and cavity modes in our setup. Lastly, the transverse mode profile of the output beam was symmetric and circular with M^2 below 1.1 in all cases.

B. Tuning the CW Laser

In this section, we will present cw laser tuning results of one SMD-pumped Cr:LiSAF laser. As mentioned earlier, tunability was achieved by rotation of a crystal quartz birefringent filter that was placed at Brewster's angle inside the laser resonator. Figure 4 shows the measured wavelength range of Cr:LiSAF using two different mirror sets (set 1 and 2) and using several different OCs. For comparison purposes, the measured unpolarized emission spectrum of the Cr:LiSAF crystal is also shown. Using curved mirror set 1 [high reflectivity (HR): 840–1100 nm] and a 1% OC [partial reflectivity (PR): 680–1100 nm], the Cr:LiSAF laser could be tuned from 784 to 1050 nm. Note that the output power varies strongly below 840 nm due to loss of reflectivity in the cavity high reflectors. Using the other curved mirror set, which had high reflectivity in the 750–850 nm range (set 2) and the same 1% OC, we obtain smooth cw lasing in the 780–890 nm range. We note here that tuning of Cr:LiSAF crystal below 780 nm is limited due to the self-absorption losses. A shoulder of the strong absorption band around 650 nm causes these losses. Self-absorption also prevent lasing below 780 nm in earlier studies with Cr:LiSAF [8,45–47]. They might be hard to overcome without using pulsed excitation and/or intracavity pumping approaches, which can lower the losses due to self-absorption via saturation effects [48].

The tuning behavior of Cr:LiSAF laser on the long wavelength side (i.e., above 1 000 nm) was investigated in detail. Previously, tuning of Cr:LiSAF has been demonstrated up to 1040 nm in the cw regime [8] and up to 1065 nm in pulsed operation [46]. However, the emission spectrum of Cr:LiSAF extends up to around 1250 nm. Hence, in our study, we have used OCs with relatively low transmission in the long wavelength side to carefully test the cw tuning limits of Cr:LiSAF. As can be seen from Fig. 4, using the 0.015% OC [partial reflectivity (PR):1090–1150 nm], we could demonstrate cw lasing of Cr:LiSAF laser up to 1110 nm. Figure 5 shows sample optical spectra recorded for laser wavelengths longer than 900 nm. To our knowledge, this is the first demonstration of cw lasing in Cr:LiSAF above 1040 nm. We note here that the mirror set we have used in this study had high reflectivity between 840 and 1100 nm. Hence, using another mirror set optimized above 1100 nm might extend the tuning range of Cr:LiSAF even further into the near infrared. On the other hand, earlier studies indicate that the excited state absorption band of Cr:LiSAF becomes stronger at longer wavelengths, which might represent the main limiting factor for tuning above 1110 nm [24].

One other point to note here is that so far the shortest pulse duration obtained from the Kerr-lens mode-locked (KLM) Cr:LiSAF laser is around 10 fs [49,50]. On these studies, the optical-spectrum of the mode-locked pulses generally only spans the 725–975 nm region due to the limited mirror

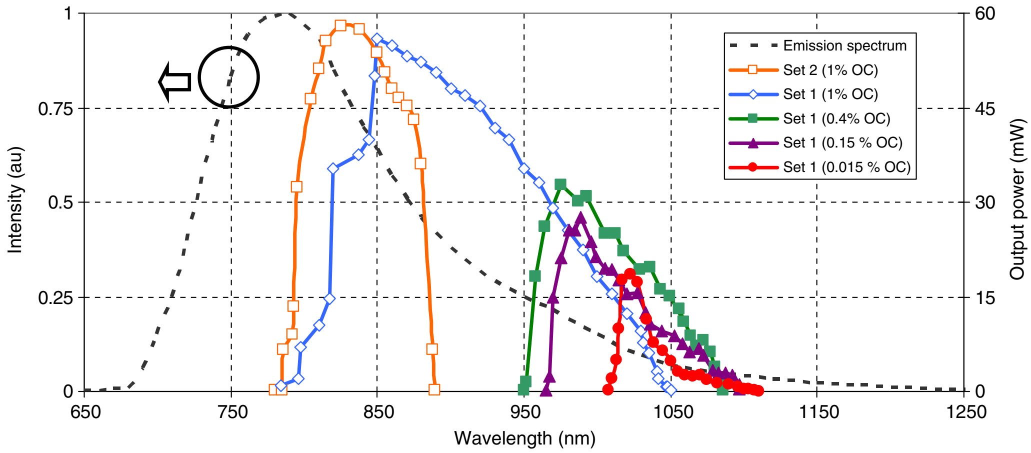

Fig. 4. (Color online) CW tuning curves for Cr:LiSAF (780–1110 nm) taken with different pump mirror sets and OCs. Mirror set 1 had high reflectivity in the 840–1100 nm range, and mirror set 2 had high reflectivity in the 750–850 nm range. The unpolarized emission spectrum of Cr:LiSAF is also shown for comparison. Working range of OCs: 0.015% OC partial reflectivity (PR) bandwidth, 1090–1150 nm; 0.15% OC PR bandwidth, 1000–1100 nm; 0.4% OC PR bandwidth, 990–1110 nm; 1% OC PR bandwidth, 680–1100 nm.

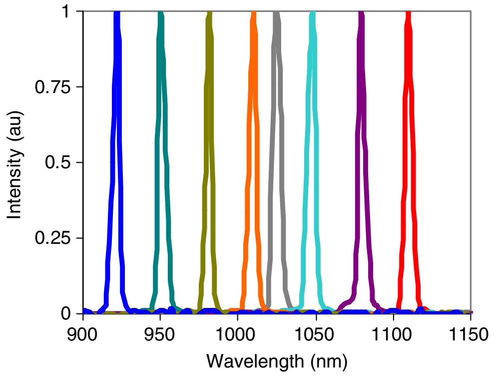

Fig. 5. (Color online) Typical optical spectra from the tunable cw Cr:LiSAF laser for wavelengths above 900 nm. The width of the spectral lines is instrument limited.

bandwidth [49]. On the other hand, the emission spectrum of Cr:LiSAF (as well as the demonstrated cw tuning range) is much broader and extends further into the infrared. Therefore, we believe that with a well-designed broadband dispersion compensating mirror set, pulses as short as 6 fs level may be feasible with KLM Cr:LiSAF lasers. Moreover, it would be also interesting to see if Cr:LiSAF lasers could be mode-locked with optical spectra centered above 1000 nm. If one can achieve that, fs Cr:LiSAF lasers may be used as a low-cost and broadband seed sources for Nd and Yb-based amplifiers.

In closing this section, we would like compare the demonstrated cw tuning range of Cr:LiSAF with other broadband gain media. Ti:sapphire has the broadest known gain bandwidth among all solid-state media. It has a demonstrated fractional tuning range of 0.57 (from 660 to 1180 nm, $\Delta\lambda/\lambda_0 \cong 0.57$, where $\Delta\lambda$ is the full width of the tuning range and λ_0 is the central wavelength) [51]. Cr:ZnSe comes very close to Ti:sapphire with a fractional tuning range of 0.56 (between 1880 and 3349 nm [48,52]). There are then several other broadly tunable gain media in the near infrared region including Cr:ZnS ($\Delta\lambda/\lambda_0 \cong 0.48$, 1962–3195 nm [52,53]), Cr:CdSe ($\Delta\lambda/\lambda_0 \cong 0.49$, 2180–3610 nm [54–56]), Fe:ZnSe ($\Delta\lambda/\lambda_0 \cong 0.21$, 3900–4800 nm [57]), and Co:MgF$_2$ ($\Delta\lambda/\lambda_0 \cong 0.35$, 1750–2500 nm [58]). However, it is clear that when one considers the central emission wavelength and the tuning bandwidth, Cr:LiSAF is the only real alternative to Ti:sapphire. With its demonstrated cw tuning range in this study (from 780 to 1110 nm), it also has one of the largest fractional tuning ranges (0.35) among all solid-state gain media. Lastly, earlier studies indicate that, using cw intracavity second harmonic generation, the tuning range of Cr:LiSAF lasers might be extended into the blue to green regions of the optical spectrum [59–62]. This spectral region is of great interest for several applications including imaging, remote atmospheric sensing, medical diagnosis, and information storage. We believe that via intracavity second harmonic generation with appropriate nonlinear crystals, the Cr:LiSAF laser system described in this work should also enable broadly tunable cw radiation in the 390–555 nm range with microwatt to milliwatt power levels.

4. MODE-LOCKED OPERATION

In this section, cw mode-locking characteristics of a Cr:LiSAF laser pumped with one SMD will be presented. We start with Table 1, which lists all results that were obtained in this study. For comparison, Table 1 also contains a comprehensive summary of mode-locking performance from the literature that was obtained with single-transverse-mode diode pumped Cr:LiSAF lasers. Note that the available power levels from SMD have improved significantly over the past years. Today, state-of-the-art specimens provide output powers as high as 200 mW. However, these diodes require active cooling. Therefore, they are avoided in this study. Moreover, unlike most of the earlier studies, which used two to six diodes for power scaling, we employ only one pump diode in this study. This choice is made to minimize cost, to reduce size, and to build a system with the lowest level of complexity. Despite this, as can be seen in Table 1, we were able to demonstrate 100 fs level pulses at repetition ranges ranging from 250 to 750 MHz and with reasonable average powers between 20 and 38 mW.

As a representative example, Fig. 6 summarizes mode-locking data of a Cr:LiSAF laser around 850 nm taken with a 0.5% OC, at the repetition rate of 235 MHz (corresponding to a cavity length of 63.5 cm). This is the lowest repetition rate we will present here. In our current study, we have tried to build relatively compact Cr:LiSAF laser systems. A 850 nm SBR was used to initiate and sustain mode-locking and DCMs were used for dispersion compensation [Fig. 1(a)]. The estimated net cavity dispersion was approximately -200 fs^2. Mode-locked laser operation was self-starting and quite robust against environmental fluctuations. A clean radio frequency (RF) spectrum was observed with the main peak at 235 MHz more than 75 dB above the noise floor [Fig. 6(c)]. Figure 6(a) shows the measured optical spectrum that was centered near 872 nm and had a spectral bandwidth of 8.5 nm. The background-free intensity autocorrelation trace had a full-width at half maximum (FWHM) of 158 fs, which corresponds to 103 fs long pulses assuming a sech^2 pulse shape [Fig. 6(b)]. The time-bandwidth product was 0.345, which is close to the transform limit of 0.315 for sech^2 pulses. At the full pump power of 130 mW, the laser produced as much as 38 mW of average mode-locked output power. This value corresponds to an output pulse energy of 162 pJ and to an output peak power of 1380 W. Note that with this high-Q cavity, the intracavity average powers were as high as 7.6 W (32.5 nJ intracavity pulse energy), and the average intracavity peak powers reached the 275 kW level. The overall efficiency of the system is remarkable. The optical-to-optical conversion efficiency was ~29% (38/130 mW), and the electrical-to-optical conversion efficiency was ~8.4% (38/450 mW). This result represents one of the highest electrical-to-optical conversion efficiencies obtained from femtosecond laser systems so far [3,5,6,28].

Using the same 0.5% OC, but with a more compact cavity of a length of 41 cm, the repetition rate of the laser was increased to 366 MHz. In this setup, the laser produced almost transform limited, self-starting pulses with a duration of 95 fs. The average output power was 32 mW, corresponding to a pulse energy of 87 pJ and a peak power of 770 W (Table 1).

We note that under identical average power levels and output coupling, the intracavity pulse energies and peak powers will decrease at higher repetition rates. In order to obtain stable cw mode-locking (without Q-switching), the intracavity pulse energy should be above a critical value [63,64]. It is clear that this critical intracavity pulse energy scales with the square root of the effective area of the laser mode on the absorber [see Eq. (16) in [63]]. Hence, to obtain stable mode-locking at higher repetition rates, one either needs to focus

Table 1. List of Average Output Powers, Peak Powers, Pulse Energies, and Pulsewidths Obtained in Mode-Locked Operation from Cr:LiSAF Oscillators Pumped with Single-Transverse-Mode Laser Diodes

Pump source	Pulse width (fs)	Pulse energy (pJ)	Peak power (W)	Average power (mW)	Reprate (MHz)	Year	Ref.
1 × 30 mW	200	1.3	6	0.23	180	97	[4]
2 × 50 mW	60	9	137	1.57	180		
2 × 50 mW	90	60	588	9	150	98	[27]
	57	43	670	6.5	150		
2 × 55 mW	136	43	276	20	470	02	[28]
4 × 55 mW	122	75	1.2×10^3	35	~210		
2 × 55 mW	151	50	292	20	~400	02	[29]
	113	38	293	15			
4 × 55 mW	146	3	18	3	1002	02	[28, 35]
4 × 55 mW	200	140	680	45	330	02	[36]
3 × 50 mW	39	756	17×10^3	6.5	8.6	03	[37]
4 × 150 mW	46	1.8×10^3	33.8×10^3	150	85	09	[8]
6 × 150 mW	55	110	1.8×10^3	110	1000	10	[38]
4 × 200 mW	26	1×10^3	38.5×10^3	85	85	11	[30]
1 × 130 mW	103	162	1.4×10^3	38	235	12	this work
	95	87	770	32	366		
	110	58	462	29	503		
	70	39	510	20	509		
	130	44	295	33	757		

on the SBR tighter or use a lower value of output coupling to keep the intracavity pulse energies at a reasonable level. For compact cavities at higher repetition rates, it is hard to obtain a very tight spot on the SBR. Therefore, we have chosen to lower the output coupling to obtain stable cw mode-locking.

To reach a repetition rate above 500 MHz, we have first reduced the output coupling from 0.5% to 0.25%. Using a 30 cm long cavity, we could obtain stable mode-locked operation with 110 fs long pulses at an average power of 29 mW (Table 1). When we further reduced the output coupling to 0.1%, the same laser cavity produced 70 fs pulses with 20 mW of average power at a repetition rate of 509 MHz (Fig. 7). The corresponding pulse energy and peak power was 39 pJ and 510 W, respectively. Note here that the average power levels in this setup are relatively low, since the parasitic cavity losses (0.3 ± 0.1)% dominate over the output coupling.

Finally, we have also tried mode-locking of a more compact cavity with a length of about 20 cm. For this variant, we have directly put the SBR in place of the flat cavity HR [Fig. 1(b)], rather than focusing on it with another curved mirror. This

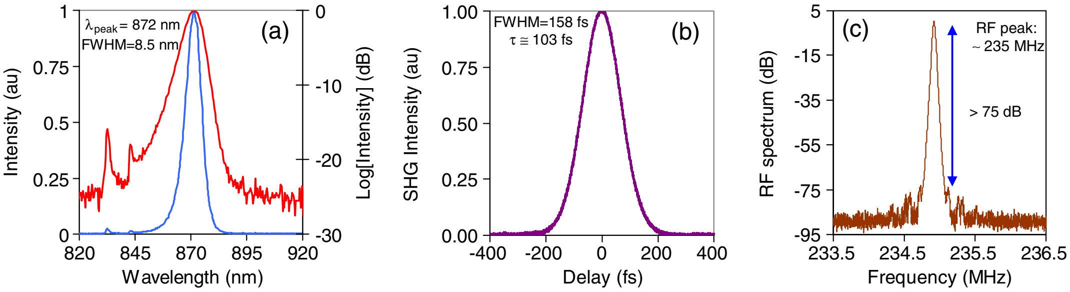

Fig. 6. (Color online) (a) Optical spectrum, (b) background-free intensity autocorrelation trace, and (c) microwave spectrum for the 103 fs, 162 pJ pulses centered around 872 nm from the Cr:LiSAF laser. This cavity had an OC of 0.5% and a repetition rate of 235 MHz.

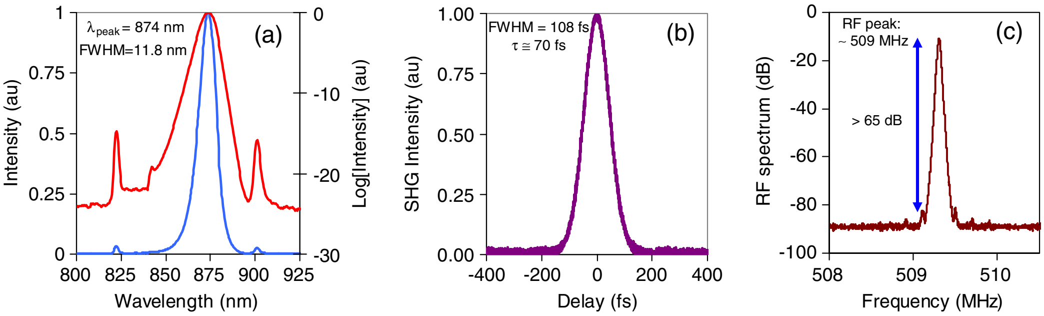

Fig. 7. (Color online) (a) Optical spectrum, (b) background-free intensity autocorrelation, and (c) microwave spectrum for the 70 fs, 35 pJ pulses centered around 874 nm from the Cr:LiSAF laser. This cavity had an OC of 0.1% and a repetition rate of 509 MHz.

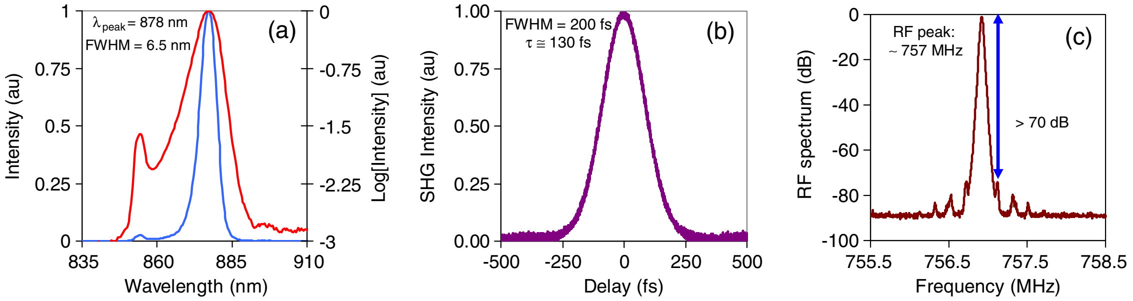

Fig. 8. (Color online) (a) Optical spectrum, (b) background-free intensity autocorrelation, and (c) microwave spectrum for the 130 fs, 44 pJ pulses centered around 878 nm from the Cr:LiSAF laser. This cavity featured an OC of 0.25% and a repetition rate of 757 MHz.

configuration enabled the construction of a more compact cavity with a reduced total number of elements. On the other hand, in this configuration, mode-locked operation was not self-staring and required shaking of one of the cavity components for initiation. The Cr:LiSAF laser then produced 130 fs pulses with 33 mW of average power at a repetition rate of 757 MHz (see Fig. 8). The corresponding peak powers in the output were approximately 300 W, which is still sufficient for several applications such as amplifier seeding. In earlier studies, repetition rates up to 1 GHz have been reported from SBR mode-locked Cr:LiSAF lasers [28,35,38]. For example, in [28,35], a Cr:LiSAF laser pumped by four 55 mw laser diodes produced 146 fs pulses with 3 mW average of power at 1 GHz repetition rate. The corresponding optical-to-optical conversion efficiency is only 1.36%. In a recent study, using six 150 mW diodes, Li *et al.* demonstrated 55 fs pulses with 110 mW average power at 1 GHz, where the corresponding optical-to-optical conversion efficiency reaches 18.3% [38]. In our current result at 750 MHz, the optical-to-optical conversion efficiency is 25.3%. Most likely, this result is due to the better mode-matching between the cavity and pump beam, as well as lower loss optics used in this study. We also note here that, unlike [38], our 750 MHz system did not require cooling of the SBR, which dramatically increases system size and complexity while deteriorating overall electrical-to-optical conversion efficiency. Lastly, it is interesting to see that a Cr:LiSAF laser pumped by only one 130 mW SMD generates high enough intracavity pulse energies for operation at a repetition rate of 750 MHz. This result shows that using Cr:LiSAF lasers pumped with higher power diodes (such as 1 W tapered devices) and using SBRs optimized for high repetition rates, it should be possible to get mode-locked cavities at repetition rates up to 5 GHz or even 10 GHz.

For the sake of completeness, we finish this section with Table 2, which presents a comprehensive summary of mode-locking results obtained from Cr:LiSAF lasers that are pumped by multimode diodes (broad-stripe single-emitter diodes, tapered diodes, and laser diode arrays). We note here that it is harder to compare multimode diode pumping results within itself, since the beam quality of multimode diodes in the slow axis varies a lot depending on the aperture size of the diode design. For example, current commercially available broad-stripe single-emitter diodes cost about $1 000, provide 1.5 W of output, and have an M^2 of about 10 in the slow axis [65]. On the other hand, recently emerging monolithic tapered diodes in the red spectral region produce 1.2 W of output and have an M^2 of only about 2.5 in the slow axis [33].

Here, due to their simplicity and lower cost, we would like to compare the results obtained with one multimode diode versus one single-transverse-mode diode pumped fs Cr:LiSAF lasers. Looking at Tables 1 and 2, we see that compared to one SMD pumping, one multimode diode pumped systems

Table 2. List of Average Output Powers, Peak Powers, Pulse Energies, and Pulsewidths Obtained in Mode-Locked Operation from Cr:LiSAF Oscillators Pumped with Multimode Laser Diodes (Broad-Stripe Single-Emitter Diodes, Tapered Diodes, and Laser Diode Arrays)

Pump source	Pulse width (fs)	Pulse energy (pJ)	Peak power (W)	Average power (mW)	Reprate (MHz)	Year	Ref.
1 × 500 mW	100×10^3	120	1.06	30	250	93	[66]
2 × 500 mW	70×10^3	8	0.07	2	250	93	[31]
2 × 400 mW	98	625	5.6×10^3	50	80	94	[67]
1 × 250 mW	97	35	300	2.7	80	94	[68]
2 × 400 mW	70	—	—	50	—	95	[69]
4 × 500 mW	40	935	20.6×10^3	70	75	95	[70]
	27	135	4×10^3	10			
2 × 400 mW	34	525	13.6×10^3	42	80	95	[71]
1 × 500 mW	100	60	550	11	178	95	[72]
2 × 500 mW	45	600	11.7×10^3	105	176	97	[73]
1 × 15 W	50	2.27×10^3	40×10^3	340	150	97	[34]
	110	3.34×10^3	26.7×10^3	500			
1 × 800 mW	26	—	—	6.2	—	97	[74]
2 × 500 mW	80	1.25×10^3	13.8×10^3	110	88	98	[75]
1 × 500 mW + 1 × 350 mW	12	32.5	2.4×10^3	6.5	200	99	[76]
1 × 500 mW + 1 × 350 mW	10	11.5	1×10^3	2.3	200	00	[25]
1 × 1.2 W	105	1.84×10^3	16.5×10^3	232	126	11	[33]

could potentially provide 5–10 times higher average (250 mW) and peak powers (15 kW). On the other hand, the multimode diodes are about 10 times more expensive, they are electrically less efficient, and, most importantly, they require water or thermoelectric cooling, which prevents the construction of portable battery powered systems. Moreover, due to the poor pump beam quality of multimode pump diodes, special pump beam collimating/shaping optics is required with multimode diodes, which makes the systems more immune to mechanical perturbations. The poor pump beam quality also creates mode-matching problems that lowers the Cr:LiSAF laser slope efficiency, and increases the thermal load on the crystal. Often, multimode diode pumped Cr:LiSAF lasers also require active cooling of the laser crystal. Furthermore, special laser cavities that necessitate cylindrical cavity mirrors and/or specially cut and coated laser crystals are used for efficient laser operation [32,34]. Hence, multimode diode pumped Cr:LiSAF lasers can provide higher average and peak powers; however, the single-transverse-mode diode pumped Cr:LiSAF laser system that we have described in this study has several key advantages in terms of cost, simplicity and compactness.

5. SUMMARY AND DISCUSSION

In this study, we have demonstrated the feasibility of developing a minimal-cost and minimal-complexity Cr:LiSAF laser that is pumped only by one state-of-the-art SMD. This device, which was originally developed for DVD technology, provides 130 mW of diffraction-limited pump power and may be driven by batteries. In cw lasing experiments, thresholds as low as 2 mW, output powers up to 58 mW, and slope efficiencies of 52% were demonstrated. To our knowledge, this result represents the lowest lasing threshold obtained from any transition-metal-doped solid-state gain medium to date. In addition, 330 nm wide smooth and continuous tuning of the Cr:LiSAF laser from 780 to 1110 nm was demonstrated. In cw mode-locking experiments with an SBR, 100 fs level pulses around 860 nm have been obtained at average powers up to 38 mW. For a repetition rate of 235 MHz, the pulse energies and peak powers were 162 pJ and 1385 kW, respectively. The repetition rate may be varied from 200 to 750 MHz via simple adjustment of cavity arm lengths. Electrical-to-optical conversion efficiencies as high as 12.8% and 8.4% were obtained in the cw and mode-locked regimes, respectively.

We note that the average powers, peak powers, and/or pulse energies demonstrated in this study could be scaled up, but at the expense of increased complexity and cost. For example, we expect that the pulse energies from this system could be increased to the 3 nJ level by building a multipass cavity with a repetition rate around 10 MHz [77,78]. Via cavity dumping, the pulse energies could be extended to the 10 nJ regime at repetition rates up to 1 MHz [79,80]. Moreover, upon pumping with tapered diodes, the average powers can be scaled to a level of 400 mW [33].

The representative mode-locking results that we presented in this study showed pulsewidths in the 70–130 fs range. However, with careful dispersion adjustment, it is possible obtain pulsewidths of ~25 fs from standard AlGaAs-based SBR mode-locked Cr:Colquiriite lasers [30]. Moreover, using novel oxidized broadband SBR mirrors [81] or Kerr-lens mode-locking with gain matched OCs [82], it might be possible to obtain sub-10 fs level pulses from Cr:LiSAF. In terms of tuning in femtosecond regime, we have only presented mode-locking with an 850 SBR. However, tunable sub-100 fs pulses from ~800 nm to ~1100 nm should be obtainable from Cr:LiSAF lasers by using several standard AlGaAs-based SBRs with different central reflectivity bandwidths (800, 850, 900, 950 nm, etc.), by using oxidized broadband SBRs [30,81], or by using carbon nanotube based saturable absorbers [83].

In conclusion, we believe that the minimal-cost and minimal-complexity Cr:LiSAF we have described in this study has several advantages in terms of compactness, energy-efficiency, portability, and cost, rendering it ideal for applications that do not require high output power levels (femtosecond amplifier seeding [39,40], optical trapping [84], short-coherence phorefractive holography [85], and optical coherence tomography [86]). Therefore, we expect that in the coming years, tunable low-cost and compact cw and femtosecond laser sources based on Cr:LiSAF will replace Ti:sapphire technology in some areas of research and applications.

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