Femtosecond Cr:Colquiriite Lasers Pumped by a Single Tapered Diode Laser

Citation: © (2012) COPYRIGHT Society of Photo-Optical Instrumentation Engineers (SPIE)Demirbas, Umit et al. "Femtosecond Cr:Colquiriite Lasers Pumped by a Single Tapered Diode Laser." Proc. SPIE 8433, Laser Sources and Applications, 84330D (June 1, 2012).

As Published: http://dx.doi.org/10.1117/12.920539

Publisher: SPIE

Persistent URL: http://hdl.handle.net/1721.1/73462

Version: Final published version: final published article, as it appeared in a journal, conference proceedings, or other formally published context

Femtosecond Cr:Colquiriite lasers pumped by a single tapered diode laser

Umit Demirbas[a,d,*], Michael Schmalz[a], Bernd Sumpf[b], Götz Erbert[b], Gale S. Petrich[c], Leslie A. Kolodziejski[c], James G. Fujimoto[c], Franz X. Kärtner[c,e], and Alfred Leitenstorfer[a]

[a]Department of Physics and Center for Applied Photonics, University of Konstanz, D-78464 Konstanz, Germany
[b]Ferdinand-Braun-Institut, Leibniz Institut für Höchstfrequenztechnik, D-12489 Berlin, Germany
[c]Department of Electrical and Computer Engineering, Massachusetts Institute of Technology, Cambridge, MA, 02139
[d]Laser Technology Laboratory, Department of Electrical and Electronics Engineering, Antalya International University, 07190 Antalya, Turkey
[e]Center for Free-Electron Laser Science, DESY and Department of Physics, University of Hamburg, D-22607 Hamburg, Germany

ABSTRACT

Ti:Sapphire lasers could provide tunable femtosecond pulses in the 680-1180 nm region; however, due to the requirement of expensive green pump sources, its current cost sets a barrier to its widespread adoption. As an alternative, Cr :Colquiriites (Cr:LiCAF, Cr:LiSAF, Cr:LiSGaF) also possess broad gain bandwidths and their total cw tuning range cover the 720-1110 nm region. Moreover, their broad absorption bands around 650 nm enable direct diode pumping by low-cost red laser diodes. However, so far the limited brightness of red diodes required combination of four to six pump diodes to reach reasonable output power levels from Cr :Colquiriites. This complex pumping geometry increases cost and causes stability issues in long-term operation. In this study, we report compact, low-cost and efficient Cr:Colquiriite lasers pumped by a single 1.2 W tapered laser diode at 675 nm. In continuous wave laser operation, output powers of 500 mW and 410 mW together with slope efficiencies of 47% and 41% were demonstrated from Cr:LiSAF and Cr:LiCAF, respectively. In cw mode-locked operation, sub-100-fs pulse trains with average power between 200 mW and 250 mW were obtained at repetitions rates around 100 MHz. These results indicate that tapered diodes in the red spectral region are likely to become the standard pump source for Cr:Colquiriite lasers in the near future. Moreover, the simplified pumping scheme might facilitate efficient commercialization of these low-cost systems, bearing the potential to significantly boost applications of cw and femtosecond lasers in this spectral region.

Keywords: Solid-state lasers, mode-locked lasers, femtosecond lasers, tunable lasers, diode pumped lasers, tapered diodes, rare earth and transition metal doped solid-state lasers, Cr:Colquiriite lasers.

1. INTRODUCTION

The Ti:Sapphire gain medium has an ultra-broad gain bandwidth that supports pulses as short as 5 fs as well as tunability from 680 to 1180 nm [1, 2]. It also exhibits favorable thermal properties which enable power scaling to several watts. Hence, Ti:Sapphire lasers successfully replaced dye laser technology in the early 1990s; and since then, they play a crucial role in the laser market, especially for applications that benefit from flexibility in wavelength, pulse duration, and average power [3]. On the other hand, Ti:Sapphire lasers are typically pumped by frequency-doubled neodymium lasers which are relatively expensive and electrically inefficient. These facts are limiting the widespread adoption of Ti:Sapphire technology and slowing down progress in many important areas of science and technology. As a promising

---

*umit79@alum.mit.edu; phone +49-(0)7531-88-2936; fax +49-(0)7531-88-3072; http://www.uni-konstanz.de/quantum-electronics

Laser Sources and Applications, edited by Thomas Graf, Jacob I. Mackenzie, Helena Jelínková, John Powell,
Proc. of SPIE Vol. 8433, 84330D · © 2012 SPIE · CCC code: 0277-786X/12/$18 · doi: 10.1117/12.920539

progress, direct diode pumping of this gain medium with blue GaN diode lasers around 450 nm has been demonstrated recently [4]. On the other hand, upon pumping with a single 1-W diode (M^2 ~1.5), 114 fs long pulses with only 13 mW of average power have been obtained in cw mode-locked operation. This result is attributed to the existence of additional parasitic losses when exciting at such short wavelengths [4]. We also note that green sources based on frequency doubled semiconductor lasers are slowly becoming the standard pump for Ti:Sapphire. Although this technology has benefits over standard Nd-based technology, the cost, complexity, and compactness are still a big issue compared to direct diode pumping.

As a promising alternative to Ti:Sapphire, Cr^{3+}-doped colquiriite crystals (Cr^{3+}:LiSAF [5], Cr^{3+}:LiSGaF [6], and Cr^{3+}:LiCAF [7]) also possess broad gain bandwidths around 800 nm, providing total tunability from 720 nm to 1110 nm and enabling generation of pulses on a 10-fs level [7-11]. More importantly, their absorption band around 650 nm allows for direct pumping by red laser diodes, significantly reducing system complexity and improving wall-plug efficiency. Various diode types have been used to pump Cr:Colquiriite lasers to date, including laser diode arrays [12], broad-stripe single-emitter diodes [13-16], and single transverse-mode laser diodes (ridge waveguide lasers) [17-25]. One main drawback of these sources has been their relatively low brightness, requiring four to six diodes to reach reasonable output power levels. For example, state-of-the-art single mode diodes at 650 nm provide about 200 mW of output power at $M^2 < 1.1$. Four of these diodes are needed to reach a cw output around 350 mW and average powers of about 250 mW in mode-locked operation [25]. Single-emitter diodes with 150 μm stripe width are commercially available and provide up to 1.5 W, but beam profiles are asymmetric and of low quality (M^2_{slow}~10, M^2_{fast}<1.1). Therefore, one needs to combine four of these diodes to reach cw output levels of 1 W and cw mode-locked average powers of about 400 mW [14, 16]. Likewise, multimode diode arrays might exhibit very high power levels (10s of Watts), but at the expense of increased cost and reduced beam quality. For example, Kopf et al. used a 15 W diode array (M^2_{sag}~1200, M^2_{tan}<1.1) to pump a specially designed Cr:LiSAF laser with an asymmetric cavity beam profile. Average powers of 1.42 W and 500 mW were obtained in cw and cw mode-locked operation, respectively [12]. In summary, all studies performed so far have used complex pumping geometries to reach reasonable output levels from Cr:Colquiriite lasers.

As an alternative technology, tapered diodes combine the excellent beam quality of ridge waveguide lasers and the output power of broad-stripe single emitters [26, 27]. Tapered diode lasers consist of a straight ridge waveguide section and a tapered section. Any higher-order modes generated in the tapered section are filtered out by the ridge waveguide, resulting in an almost diffraction-limited beam profile [26]. For example, tapered diodes at 980 nm have been successfully used for pumping solid-state lasers based on Ytterbium and Neodymium [28, 29]. Note that there exist devices based on the master oscillator power amplifier (MOPA) concept. In contrast to MOPA systems with several independent components operated in series, the entire chip acts as a resonator in tapered diodes [26]. In 1998, Robertson et al. used two hybrid MOPA devices providing 450 mW of output power each (M^2 <2) to pump a Cr:LiSAF laser. They obtained femtosecond pulse trains with approximately 100 mW of average power and a tuning range from 809 nm to 910 nm [30].

In this work, we report the first successful application of monolithic tapered diode lasers to pump Cr:Colquiriite systems [31]. A single device on a c-mount package was used [27]. It provided up to 1.2 W of output power at 675 nm together with M^2 values of 1.5 in the fast axis and 2.5 in the slow axis, respectively. Up to 500 mW and 410 mW of output power and slope efficiencies of 47% and 41% were demonstrated from Cr:LiSAF and Cr:LiCAF lasers in cw operation at 1150 mW of absorbed pump power, respectively. Mode locking was initiated and sustained with saturable absorber mirrors (SESAMs/SBRs) [32, 33]. In typical mode locking experiments, 105-fs, 1.84-nJ pulses with 232 mW of average power around 800 nm, and 90-fs, 1.97-nJ pulses with 193-mW of average power around 850 nm have been obtained from the Cr:LiSAF laser. Similarly, in mode-locking experiments with Cr:LiCAF, 55-fs, 2.04-nJ pulses with 217 mW of average power around 800 nm have been achieved. These results show that Cr:Colquiriite lasers pumped with tapered diodes are arising as attractive alternatives to Ti:Sapphire for various applications in science and technology such as e.g. multiphoton microscopy.

2. EXPERIMENTAL SETUPS

Figure 1 shows the setups of the Cr:LiSAF and Cr:LiCAF lasers under study. The gain medium was pumped at 675 nm by a single, linearly-polarized (TM) tapered diode laser providing up to 1180 mW of power at a drive current of 1.5 A, a base temperature of 15 °C and a conversion efficiency of approximately 30 % [27]. The output of the diode was collimated by an aspheric lens of a focal length of f = 4.5 mm and a cylindrical lens with f_z = 50 mm. An achromatic doublet with f = 60 mm was used to focus the pump beam into the crystals. Astigmatically-compensated, X-cavities with two curved pump mirrors (M1 and M2, R = 75 mm or 100 mm), a flat end mirror (M3), and a flat output coupler (OC) were employed in the cw laser experiments. The length of the long cavity arm was adjusted to obtain a beam waist of approximately 25 µm inside the gain medium. A 7-mm-long, 1.5% Cr-doped Cr:LiSAF and a 4-mm-long, 7% Cr-doped Cr:LiCAF crystal from VLOC were used in the studies. They absorbed 99.5% and 98.5% of the incident TM polarized pump light at 675 nm, respectively. Both crystals were 1.5 mm thick and mounted with indium foil in a copper holder under water cooling.

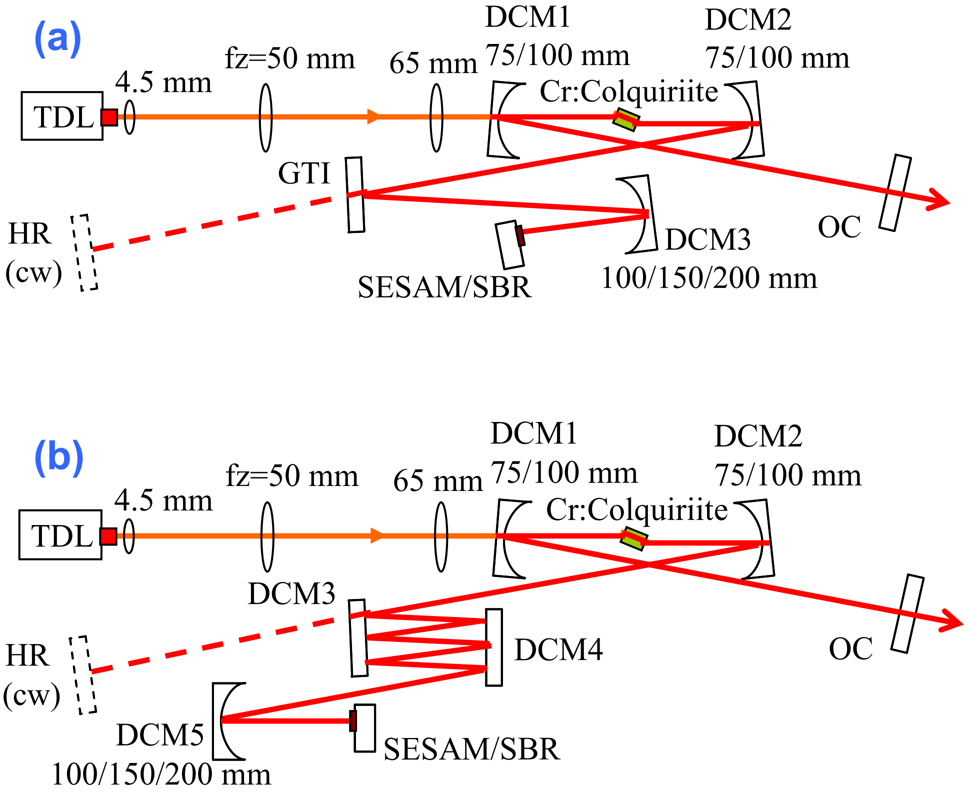

Figure 1. Schematics of cw and mode-locked Cr:LiCAF & Cr:LiSAF oscillators pumped by a single tapered diode laser (TDL). Double chirped mirrors (DCMs, bottom), as well as a combination of a Gires–Tournois interferometer (GTI) and DCMS (top) are used for dispersion compensation.

For mode-locked operation, dispersion compensation was performed via DCMs, partially in combination with a GTI. The DCMs used in this study had group delay dispersion (GDD) of -50 fs^2 or -80 fs^2 per bounce, respectively. The GTI mirror provided a GDD of -550±50 fs^2 per bounce in the spectral range between 790 and 820 nm. Two different AlGaAs-based SESAMs/SBRs with centered reflectivity around 800 and 850 nm were used to initiate and sustain mode-locking. Modulation depths amounted to (0.8±0.2)% and (0.6±0.15)%, respectively. Detailed information on these devices may be found in [25].

3. RESULTS OF CONTINUOUS-WAVE LASING EXPERIMENTS

The cw laser efficiencies of Cr:LiSAF and Cr:LiCAF at various levels of output coupling are depicted in Figure 2. All data were taken at a base temperature of the crystal mount of 18 °C. With both gain media, almost identical results were obtained using 0.5 and 1% output couplers. Due to the increased role of thermal effects, obtainable power levels decreased under 2 and 3 % of output coupling. An output power as high as 500 mW was obtained at an absorbed pump of 1145 mW with Cr:LiSAF using the 0.5% OC. The corresponding lasing threshold and the slope efficiency were 45 mW and 47%, respectively. Our estimate of the total cavity losses per round trip of approximately 0.8 % is based on measuring the lasing threshold with different output couplers. The slope efficiency of our Cr:LiSAF laser comes close to the reported intrinsic value from the literature of 54% [16]. This fact highlights good mode-matching between the pump and cavity modes in our setup. An output of 410 mW was obtained with the Cr:LiCAF laser at an absorbed pump power of 1115 mW and under a value of 0.5 % of output coupling. A lasing threshold of 93 mW and a slope efficiency of 41% have been determined for this system. As indicated by the lower output level, the total round trip losses were estimated to be approximately 1.5 % for the Cr:LiCAF cavity. We expect the performance to further improve in future studies with lower-loss Cr:LiCAF crystals.

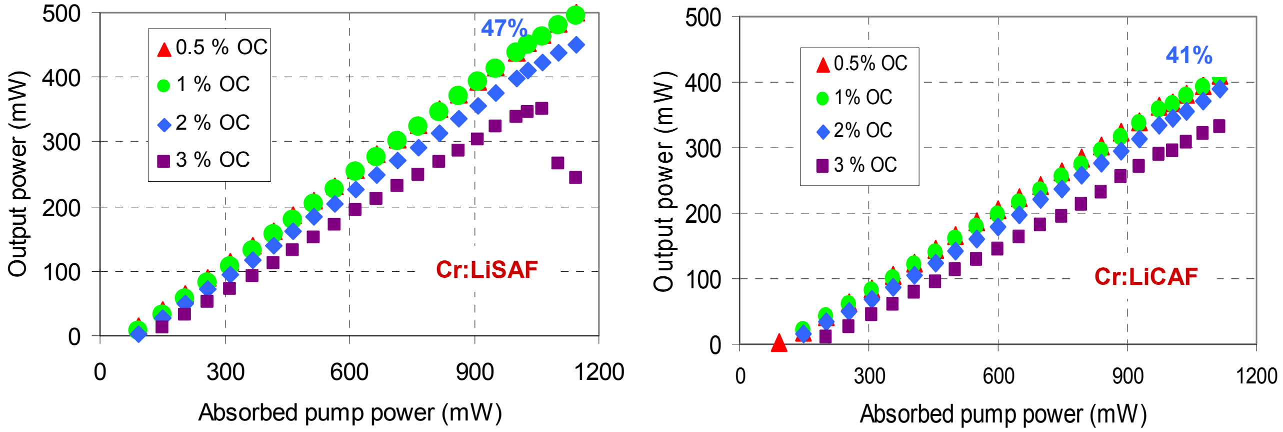

Figure 2. Continuous-wave output power versus absorbed pump power for the tapered diode pumped Cr:LiSAF (left) and Cr:LiCAF (right) lasers taken at various levels of output coupling between 0.5% and 3%.

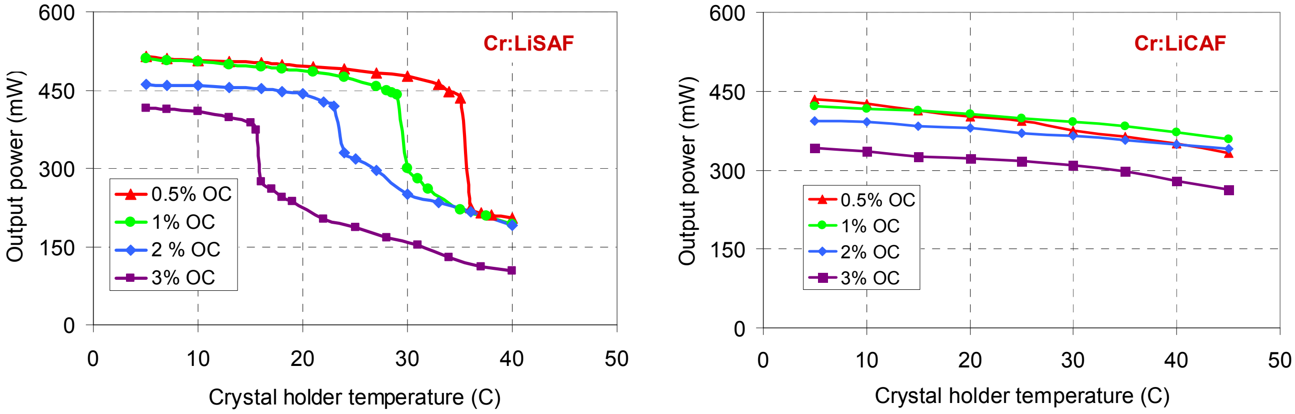

Figure 3. Laser output power under continuous-wave operation at various levels of output coupling (OC) as a function of the temperature of the cooling water for the crystal holder for Cr:LiSAF (left) and Cr:LiCAF (right). The absorbed pump power was kept at a value of 1150 mW.

We have also investigated the effects of thermal loading on the laser crystals. This information was gained by measuring the cw laser performance at varying temperatures of the crystal holder and with different output couplers. Figure 3 shows the measured cw laser output powers versus base temperature for the Cr:LiSAF and Cr:LiCAF lasers, at an absorbed pump power level of 1150 mW. The results show that thermal effects are less pronounced in Cr:LiCAF due to its superior thermal properties as compared to Cr:LiSAF (i.e. higher thermal conductivity, as well as lower quantum defect, excited-state absorption and upconversion rate [16]). Even though there is some increase in Cr:LiCAF laser output power upon cooling, our results show that the improvements are of minor importance and the tapered diode pumped Cr:LiCAF laser can be operated efficiently at room temperature. On the other hand, a very different and interesting behavior is observed with the Cr:LiSAF. First of all, for each output coupling there is a critical temperature at which the laser power decreases abruptly. This finding indicates that the local temperature in some part of the Cr:LiSAF crystal reaches ~70 °C which represents a critical threshold for lifetime quenching [16]. The decrease in upper state lifetime limits the level of output power. Secondly, the thermal effects are worse at high values of output coupling. This observation results from an Auger upconversion process in Cr:Colquiriites [16, 34-36]: the lifetime of the upper laser level not only depends on temperature but also on the degree of inversion. Application of higher output coupling decreases the intracavity power which results in an increase of the population inversion of the upper laser level. In turn the upper state lifetime decreases and laser performance gets degraded [16]. Note that the laser is conveniently operated at room temperature using low output coupling.

4. PERFORMANCE OF MODE-LOCKED OPERATION

In this section, representative cw mode-locking results from the tapered diode pumped Cr:LiSAF and Cr:LiCAF lasers are presented. In all cases, we kept the repetition rates around 100 MHz and the pulsewidths around 100 fs or below. Those are typical parameters desired for interesting applications like e.g. multiphoton microscopy [37]. From the tapered diode pumped Cr:LiSAF laser, we have obtained almost transform limited 105-fs long pulses centered around 865 nm using an 850 nm SESAM/SBR to initiate mode-locking and DCMs for dispersion compensation. An average output as high as 232 mW was achieved at an absorbed pump power of 1 W (see Fig. 4). The transverse mode profile was symmetric and circular with M^2 below 1.1. For the data depicted in Fig. 4(a), the crystal holder was cooled to 10 °C and the maximum output power was ultimately limited by thermal effects. Similarly, using a 1% output coupler, the 800-nm SBR and a GTI mirror, we have obtained a train of 90-fs pulses centered at 810 nm with an average power of 193 mW (Fig. 5). Interestingly, thermal effects still limited the obtainable average powers even with the 1% output coupler and at a crystal base temperature of 10 °C. We attribute this finding to the increased losses of the mode-locked laser cavity. Consequently, special low-loss DCM/GTI mirrors and SESAM/SBRs will be required for optimum operation of tapered diode pumped Cr:LiSAF lasers in the mode-locked regime.

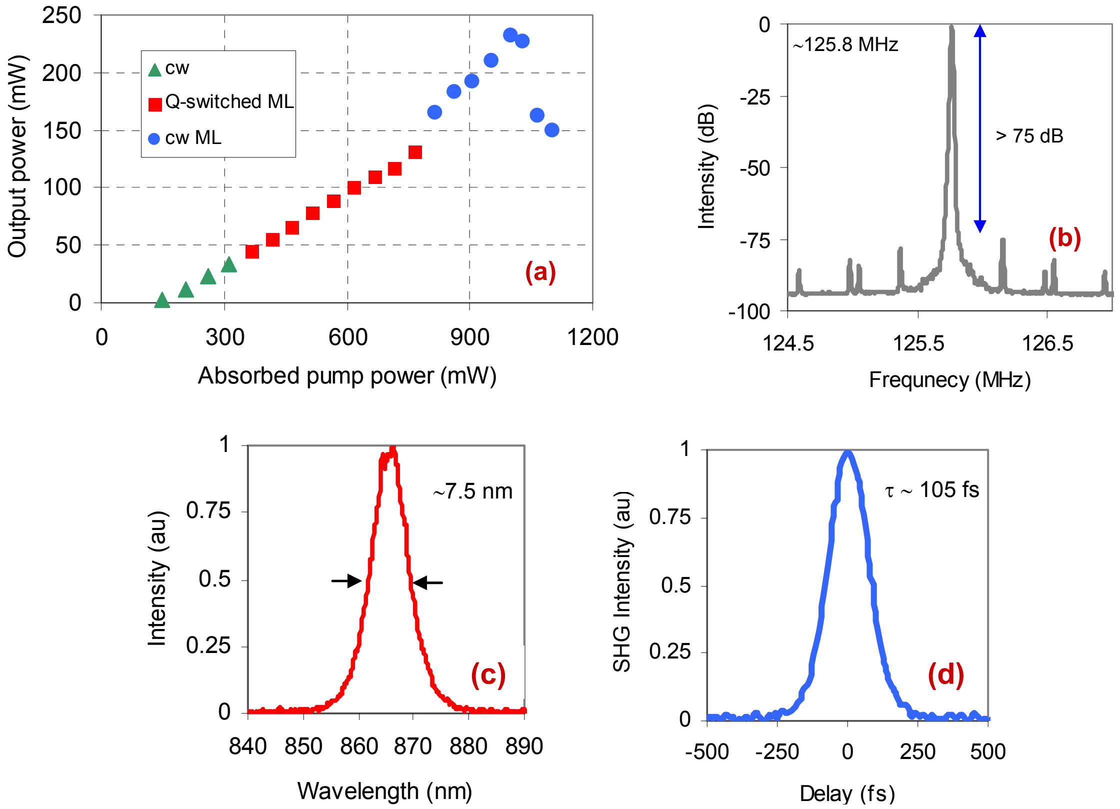

Figure 4. Output power versus absorbed pump power (a), microwave spectra (b), optical spectrum (c), and autocorrelation trace (d) for the 105 fs, 1.84 nJ pulses centered around 865 nm from the Cr:LiSAF laser. The laser featured a 3% output coupler and a repetition rate of 125.8 MHz.

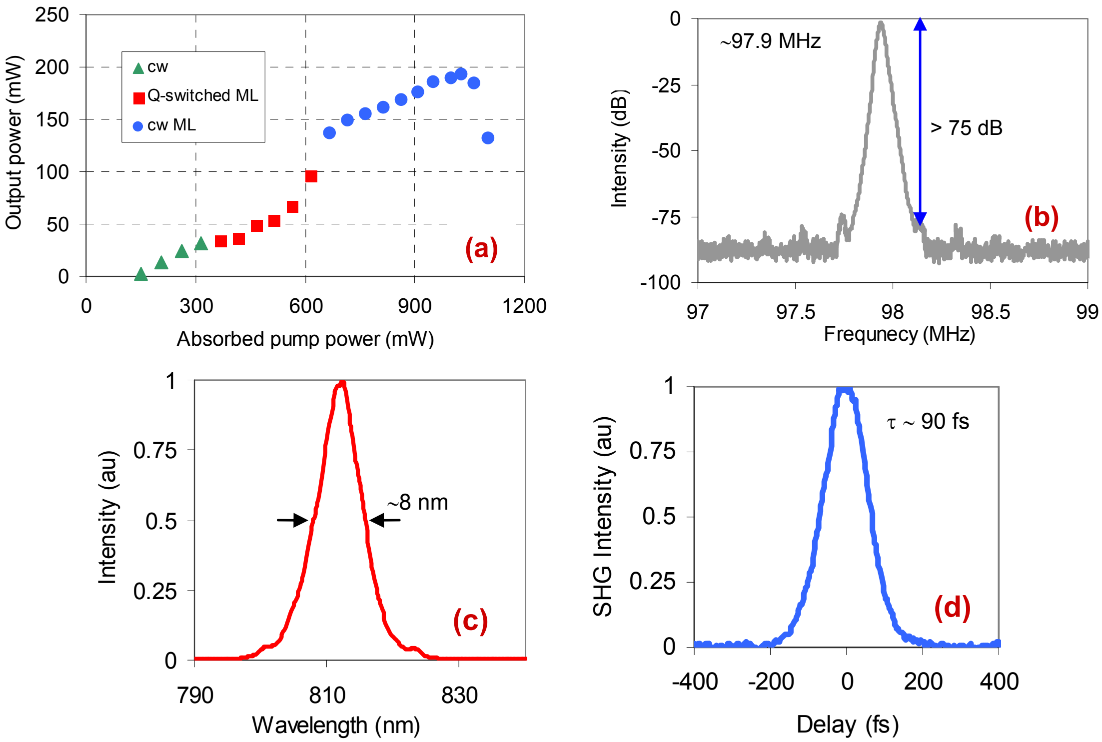

Figure 5. Output power versus absorbed pump power (a), microwave spectra (b), optical spectrum (c), and autocorrelation trace (d) for the 90 fs, 1.97 nJ pulses centered around 810 nm from the Cr:LiSAF laser. This cavity had an output coupler of 1% and a repetition rate of 97.9 MHz.

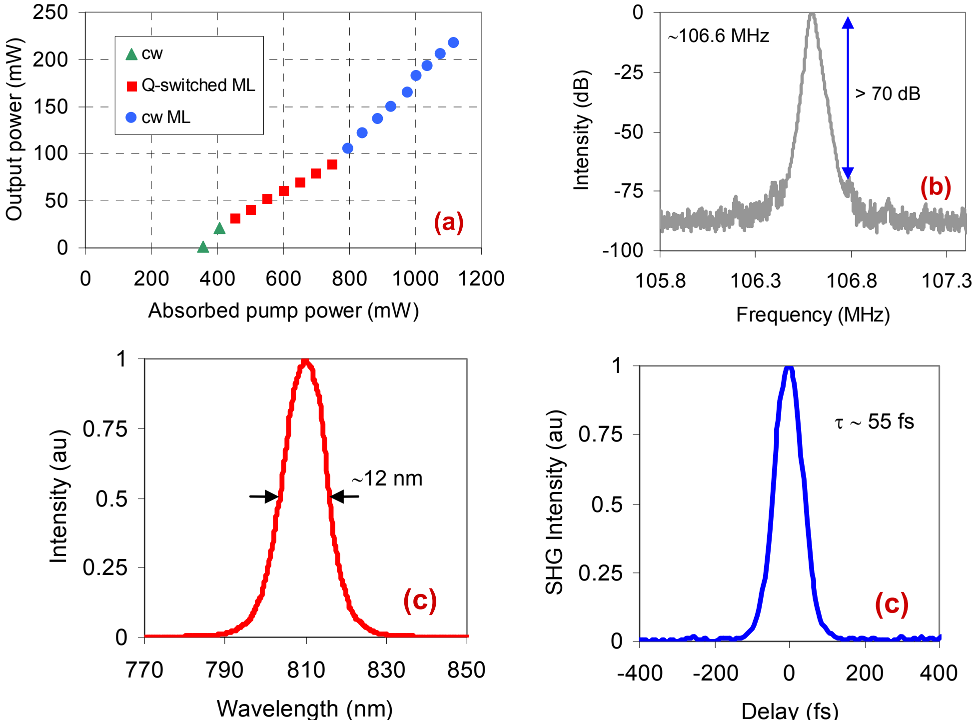

Figure 6. Output power versus absorbed pump power (a), microwave spectra (b), optical spectrum (c), and autocorrelation trace (d) for the 55 fs, 2.04 nJ pulses centered around 810 nm from the Cr:LiCAF laser. The laser had a 2% output coupler and a repetition rate of 106.6 MHz.

In mode-locking experiments with the Cr:LiCAF laser, under 2% of output coupling, using DCM mirrors for dispersion compensation and the 800-nm SBR for mode-locking, we have obtained pulse durations as short as 55 fs and an average output of 217 mW at an absorbed pump power of 1115 mW (Fig. 6). Motivated by the superior thermal properties of the Cr:LiCAF crystal, the crystal holder was cooled to only 18 °C. Still, we did not observe a significant limitation in obtainable output powers due to thermal effects.

5. SUMMARY

In summary, we have presented cw and cw mode-locked operation of Cr:LiSAF and Cr:LiCAF lasers pumped by a tapered diode laser. Our results show that a single pump device is sufficient to reach attractive levels of output power. Moreover, compared to systems that are pumped by four single or multimode diodes, the tapered diode pumped system is compact, less complex and therefore features reduced alignment sensitivity and enhanced long-term stability. Therefore, we are convinced that such low-cost tapered diodes in the red spectral region will become the standard pump source for Cr:Colquiriite lasers in the near future. We have observed some thermal effects in Cr:LiSAF, but there is great potential to reduce them in future studies by using thinner gain crystals and intracavity optics with lower loss. In short, with its favorable output characteristics, our compact Cr:Colquiriite systems represent attractive alternatives to Ti:Sapphire technology in emerging applications requiring near-infrared femtosecond pulse trains.

ACKNOWLEDGMENTS

We thank Christian Beschle, Günther Krauss, Daniele Brida, Stefan Eggert, Sören Kumkar and Marcel Wunram from Konstanz University, Alphan Sennaroglu from Koç University, and Duo Li, Jing Wang, Sheila Nabanja, Peter Fendel, and Jonathan Birge from Massachusetts Institute of Technology for their help. We acknowledge partial support from the Center for Applied Photonics of Konstanz University, and by AFOSR contracts FA9550-10-1-0063 and FA9550-07-1-0101, NSF ECCS-0900901 and Thorlabs Inc. Umit Demirbas acknowledges postdoctoral fellowship support from Alexander von Humboldt-Foundation.

REFERENCES

[1] P. F. Moulton, "Spectroscopic and laser characteristics of Ti:Al_2O_3," JOSA B, 3(1), 125-133 (1986).

[2] R. Ell, U. Morgner, F. X. Kärtner *et al.*, "Generation of 5 fs pulses and octave-spanning spectra directly from a Ti:sapphire laser," Optics Letters, 26, 373-375 (2001).

[3] J. Klein, and J. D. Kafka, "The Ti:Sapphire Laser: The flexible research tool," Nature Photonics, 4(5), 289 (2010).

[4] P. W. Roth, A. J. Maclean, D. Burns *et al.*, "Direct diode-laser pumping of a mode-locked Ti:Sapphire laser," Optics Letters, 36(2), 304-306 (2011).

[5] S. A. Payne, L. L. Chase, L. K. Smith *et al.*, "Laser performance of $LiSAIF_6$:Cr^{3+}," Journal of Applied Physics, 66(3), 1051-1056 (1989).

[6] L. K. Smith, S. A. Payne, W. L. Kway *et al.*, "Investigation of the laser properties of Cr^{3+}:$LiSrGaF_6$," IEEE Journal of Quantum Electronics, 28, 2612-2618 (1992).

[7] S. A. Payne, L. L. Chase, H. W. Newkirk *et al.*, "$LiCaAlF_6$:Cr^{3+} a promising new solid-state laser material," IEEE Journal of Quantum Electronics, 24(11), 2243-2252 (1988).

[8] J. F. Pinto, L. Esterowitz, and G. H. Rosenblatt, "Frequency tripling of a Q-switched Cr:LiSAF laser to the UV region," IEEE Journal of Selected Topics in Quantum Electronics, 1(1), 58-61 (1995).

[9] I. T. Sorokina, E. Sorokin, E. Wintner *et al.*, "14-fs pulse generation in Kerr-lens mode-locked prismless Cr:LiSGaF and Cr:LiSAF lasers: observation of pulse self-frequency shift," Optics Letters, 22(22), 1716-1718 (1997).

[10] S. Uemura, and K. Torizuka, "Generation of 10 fs pulses from a diode-pumped Kerr-lens mode-locked Cr : LiSAF laser," Japanese Journal of Applied Physics Part 1-Regular Papers Short Notes & Review Papers, 39(6A), 3472-3473 (2000).

[11] P. Wagenblast, U. Morgner, F. Grawert *et al.*, "Generation of sub-10-fs pulses from a Kerr-lens modelocked Cr^{3+}:LiCAF laser oscillator using third order dispersion compensating double chirped mirrors," Optics Letters, 27, 1726-1729 (2002).

[12] D. Kopf, K. J. Weingarten, G. Zhang *et al.*, "High-average-power diode-pumped femtosecond Cr:LiSAF lasers," Applied Physics B-Lasers and Optics, 65(2), 235-243 (1997).

[13] P. M. W. French, R. Mellish, J. R. Taylor *et al.*, “Mode-locked all-solid-state diode-pumped Cr:LiSAF Laser,” Optics Letters, 18(22), 1934-1936 (1993).

[14] A. Isemann, and C. Fallnich, “High-power colquiriite laser with high slope efficiencies pumped by broad-area laser diodes.,” Optics Express, 11, 259-264 (2003).

[15] P. Wagenblast, R. Ell, U. Morgner *et al.*, “Diode-pumped 10-fs Cr^{3+}: LiCAF laser,” Optics Letters, 28(18), 1713-1715 (2003).

[16] U. Demirbas, A. Sennaroglu, F. X. Kärtner *et al.*, “Comparative investigation of diode pumping for continuous-wave and mode-locked Cr^{3+}:LiCAF lasers ” Journal of Optical Society of America B, 26(1), 64-79 (2009).

[17] R. Scheps, J. F. Myers, H. B. Serreze *et al.*, “Diode-pumped Cr:$LiSrAlF_6$ laser,” Optics Letters, 16(11), 820-822 (1991).

[18] S. Tsuda, W. H. Knox, and S. T. Cundiff, “High efficiency diode pumping of a saturable Bragg reflector-mode-locked Cr:LiSAF femtosecond laser,” Appl. Phys. Lett., 69, 1538-1540 (1996).

[19] G. J. Valentine, J. M. Hopkins, P. Loza-Alvarez *et al.*, “Ultralow-pump-threshold, femtosecond Cr^{3+}:$LiSrAlF_6$ laser pumped by a single narrow-stripe AlGaInP laser diode,” Optics Letters, 22(21), 1639-1641 (1997).

[20] J. M. Hopkins, G. J. Valentine, W. Sibbett *et al.*, “Efficient, low-noise, SESAM-based femtosecond Cr^{3+}: $LiSrAlF_6$ laser,” Optics Communications, 154(1-3), 54-58 (1998).

[21] B. Agate, B. Stormont, A. J. Kemp *et al.*, “Simplified cavity designs for efficient and compact femtosecond Cr:LiSAF lasers,” Optics Communications, 205(1-3), 207-13 (2002).

[22] J. M. Hopkins, G. J. Valentine, B. Agate *et al.*, “Highly compact and efficient femtosecond Cr : LiSAF lasers,” Ieee Journal of Quantum Electronics, 38(4), 360-368 (2002).

[23] D. Li, U. Demirbas, J. R. Birge *et al.*, “Diode-pumped passively mode-locked GHz femtosecond Cr:LiSAF laser with kW peak power,” Optics Letters, 35(9), 1446-1448 (2010).

[24] U. Demirbas, A. Sennaroglu, F. X. Kärtner *et al.*, “Generation of 15 nJ pulses from a highly efficient, low-cost multipass-cavity Cr^{3+}:LiCAF laser,” Optics Letters, 34(4), 497-499 (2009).

[25] U. Demirbas, G. S. Petrich, D. Li *et al.*, “Femtosecond tuning of Cr:Colquiriite lasers with AlGaAs-based saturable Bragg reflectors,” JOSA B, 28(5), 986-993 (2011).

[26] B. Sumpf, K. H. Hasler, P. Adamiec *et al.*, “High-brightness quantum well tapered lasers,” IEEE Journal of Selected Topics in Quantum Electronics, 15(3), 1009-1020 (2009).

[27] B. Sumpf, P. Adamiec, M. Zorn *et al.*, “Nearly Diffraction Limited Tapered Lasers at 675 nm with 1 W Output Power and conversion efficiencies above 30%,” IEEE Photonics Technology Letters, 22(99), 266-268 (2011).

[28] P. Klopp, V. Petrov, U. Griebner *et al.*, “Passively mode-locked Yb:KYW laser pumped by a tapered diode laser,” Optics Express, 10(2), 108-113 (2002).

[29] H. P. H. Cheng, O. B. Jensen, P. Tidemand-Lichtenberg *et al.*, “Efficient quasi-three-level Nd:YAG laser at 946 nm pumped by a tunable external cavity tapered diode laser ” Optics Communications, 283(23), 4717-4721 (2010).

[30] A. Robertson, R. Knappe, and R. Wallenstein, “Diode-pumped broadly tunable (809-910 nm) femtosecond Cr : LiSAF laser,” Optics Communications, 147(4-6), 294-298 (1998).

[31] U. Demirbas, M. Schmalz, B. Sumpf *et al.*, “Femtosecond Cr:LiSAF and Cr:LiCAF lasers pumped by tapered diode lasers,” Optics Express, 19(21), 20444-20461 (2011).

[32] U. Keller, K. J. Weingarten, F. X. Kärtner *et al.*, “Semiconductor saturable absorber mirrors (SESAM's) for femtosecond to nanosecond pulse generation in solid-state lasers,” IEEE Journal of Selected Topics in Quantum Electronics, 2(3), 435-453 (1996).

[33] S. Tsuda, W. H. Knox, S. T. Cundiff *et al.*, “Mode-locking ultrafast solid-state lasers with saturable Bragg reflectors,” Ieee Journal of Selected Topics in Quantum Electronics, 2(3), 454-464 (1996).

[34] F. Balembois, F. Falcoz, F. Kerboull *et al.*, “Theoretical and experimental investigations of small-signal gain for a diode-pumped Q-Switched Cr:LiSAF laser,” Ieee Journal of Quantum Electronics, 33(2), 269-278 (1997).

[35] J. M. Eichenholz, and M. Richardson, “Measurement of thermal lensing in Cr^{3+}-doped colquiriites,” IEEE Journal of Quantum Electronics, 34(5), 910-919 (1998).

[36] M. Stalder, M. Bass, and B. H. T. Chai, “Thermal quenching of fluoresence in chromium-doped fluoride laser crystals,” Journal of Optical Society of America B, 9(12), 2271-2273 (1992).

[37] S. Sakadžić, U. Demirbas, T. R. Mempel *et al.*, “Multi-photon microscopy with a low-cost and highly efficient Cr:LiCAF laser,” Optics Express, 16(25), 20848–20863 (2008).