Highly efficient and robust operation of Kerr-lens mode-locked Cr:LiSAF lasers using gain-matched output couplers

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We present efficient and robust Kerr-lens mode locking (KLM) of a diode-pumped Cr:LiSAF laser using a gain-matched output coupler (GMOC). An inexpensive, battery-powered 660 nm single-spatial-mode diode was used as the pump source. GMOC enhances the effective self-amplitude modulation depth by reducing the gain-filtering effect in broadband KLM operation to provide significant improvement in efficiency and robustness. Pulsing can be initiated without careful cavity alignment and is sustained for hours. 13 fs pulses with an average power of 25 mW have been generated using only 120 mW of pump power. The corresponding pulse energy and peak power is 200 pJ and 15 kW for the 126 MHz repetition rate cavity. Optical-to-optical conversion efficiency of the system is 21%, which represents an order of magnitude improvement in reported efficiencies for such diode-pumped ultrashort-pulse KLM Cr:LiSAF lasers. The obtainable pulse width is currently limited by the dispersion bandwidth of the available optics and can be potentially reduced to below 7 fs.

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Kerr-lens mode locking (KLM) is a flexible and versatile passive mode-locking mechanism that is frequently employed in ultrashort-pulse generation [1–5]. It is based on Kerr-nonlinearity-induced fast-saturable-absorber action caused by an instantaneous lensing effect. The saturable absorber shortens the circulating intracavity pulse via self-amplitude modulation (SAM) until it is balanced by the gain filtering effect. Due to the broadband nature of Kerr nonlinearity, KLM does not impose any practical bandwidth limitation on the obtainable pulsewidth (unlike resonant saturable absorber mirrors [6]). Hence, KLM operation is especially attractive for ultra-broadband gain media such as Ti:Sapphire [1,3], Cr:LiSAF [2,4], Cr:Forsterite and Cr:ZnSe [5], where mode locking with regular saturable absorber mirrors limits the obtainable pulse widths [6].

To attain the shortest pulses via KLM, a flat dispersion profile over the whole gain bandwidth of the material should be utilized. Moreover, the strong gain filtering effect of the active medium should be overcome. This second requirement necessitates a large SAM, which involves the use of high pump powers, low output coupling, critical cavity alignment, and, in most cases, operation near the edge of the stability region. However, fulfilling these requirements may result in lower laser efficiency, high mode-locking threshold, long-term stability problems, and reduced output beam quality.

The requirements mentioned above are especially challenging in gain media with a low nonlinear refractive index (n_2) such as Cr:LiSAF ($n_2 = 0.8 \times 10^{-16}$ cm^2/W, which is four times lower than that for Ti:Sapphire and 200 times lower than that for Cr:ZnSe [5]). Cr:LiSAF can be directly diode-pumped by low-cost diodes in the red spectral region and has an ultra-broad gain bandwidth, covering the wavelength range at least from 780 to 1110 nm and potentially enabling sub-7-fs pulse generation [7,8]. Hence it is actually an ideal low-cost alternative to Ti:Sapphire. However, so far, Cr:LiSAF lasers could not be developed beyond laboratory demonstrations due to the above-mentioned problems. Even though pulses as short as 10 fs have been demonstrated from low-cost diode-pumped Cr:LiSAF lasers, long-term stability has been a problem, and efficiencies were limited to below 2% for sub-30-fs pulses [4,9].

Overcoming the limitations imposed by KLM requires the minimization of the gain filtering effect. For an ideal case, in a cavity without any gain filtering, even weak KLM action could sustain ultrashort pulses, and this would ideally prevent all of the above-mentioned problems. In a recent study, Chen *et al.* showed that use of gain-matched output couplers (GMOC) with a transmission profile that matches the gain spectrum of the laser active medium cancels out the gain filtering effect [10]. In this method, the GMOC mirror creates a loss profile that has the same shape as the cavity gain, which results in a broadband flat net gain. As a result, the need for strong SAM is reduced, and even a low level of KLM action is sufficient to sustain ultrashort pulses. In their work, Chen *et al.* demonstrated robust mode locking of Ti:Sapphire with sub-8-fs pulses at greatly reduced Kerr nonlinearity requirements using a 4% GMOC [10].

In this work, we report, for the first time to our knowledge, the robust and efficient KLM operation of a diode-pumped, low-cost Cr:LiSAF laser with a GMOC mirror. A 130 mW, 650 nm SMD with a diffraction-limited output was used as the pump source. KLM operation did not require critical cavity alignment and could be initiated at incident pump powers as low as 50 mW. Once initiated, the laser remained mode-locked for hours. Using double-chirped mirrors (DCMs) and a fused silica prism pair for dispersion compensation, we could obtain sub-15-fs pulses with 25 mW average power at an incident pump power of 120 mW. The repetition rate was around 126 MHz, and the corresponding pulse energy and peak power reached 200 pJ and 15 kW levels, respectively. Optical-to-optical conversion efficiency of the system was 21%, which represents an order of magnitude improvement compared to earlier results. Moreover, the system had an estimated material cost below $5 k, an electrical-to-optical conversion efficiency of around 7%, a footprint of only 30 cm × 40 cm, and could be powered with 8 AA-type batteries for 10 h. The obtainable pulsewidth in this study is currently limited by the dispersion bandwidth of the available optics and can be potentially reduced to below 7 fs in a dispersion-optimized cavity. In short, this study demonstrates that the GMOC mirror greatly reduces the requirements of Kerr lens mode locking even in gain media with a low n_2 like Cr:LiSAF and, as a result, significantly improves the long-term stability as well as the efficiency of the laser.

Figure 1 shows a schematic of the KLM Cr:LiSAF laser that was employed in this study. The pump diode output was first collimated with a 4.5 mm focal length aspheric lens (f1) and then focused into the crystal using an achromatic doublet (f2, 60 mm). The 6 mm long Cr:LiSAF crystal was 1.5% Cr-doped and absorbed around 98% of the incident pump power. The laser cavity consisted of two curved pump mirrors (M1, M2, ROC = 75 mm), the GMOC mirror, and a flat high reflector (M3). The GMOC mirror, which was actually designed for Ti:Sapphire, had a transmission of around 0.7% around the gain peak and on the long wavelength side, its spectral transmission profile matched the gain profile of Cr:LiSAF quite well (Fig. 2). The curved pump mirrors and the cavity high reflector were custom-made double-chirped mirrors (DCM, M1-M3) with a transmission above 98% from 625 to 685 nm to transmit the pump beam. Their reflectivity was above 99.9% from 790 to 940 nm and provided around -80 ± 10 fs^2 of group delay dispersion (GDD) per bounce in the 780–950 nm wavelength range. A fused silica prism pair with a separation of 30 cm also was used to fine-tune the net cavity dispersion. The GMOC mirror was mounted on a rail, and mode locking could be initiated by slightly changing the GMOC mirror position.

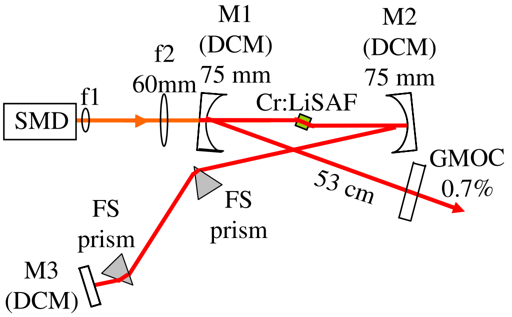

Fig. 1. Schematic of the single-mode diode (SMD) pumped Kerr-lens mode-locked Cr:LiSAF laser with a GMOC. For dispersion compensation, DCM and a fused silica prism pair with a separation of 30 cm were used. Cavity arm lengths were 53 and 57 cm.

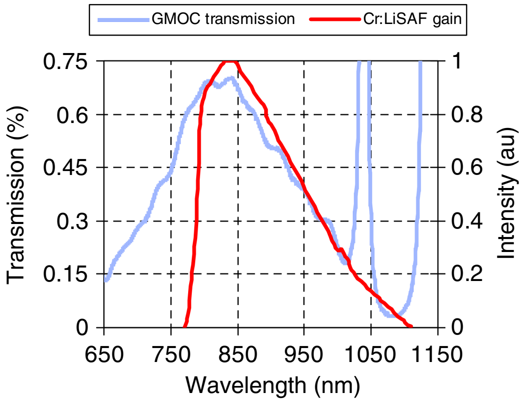

Fig. 2. Gain profile of the Cr:LiSAF crystal and the designed transmission spectrum of the GMOC.

Figure 3 shows the measured variation of the Cr:LiSAF laser output power as a function of the incident pump power. Data with the circular markers were taken near the center of the outer stability range, where the continuous-wave (cw) laser power was optimized (cw in Fig. 3). For this case, the measured cw lasing threshold and laser slope efficiency were 13 mW and 35%, respectively. Earlier, a lasing threshold of 8 mW and a slope efficiency of 50% were reported from a similar cavity [8]. The slight decrease in the cw laser performance in this study is due to the additional losses associated with the DCM mirrors and the prism pair.

To test the effectiveness of the GMOC, we also measured the variation of the threshold pump power with lasing wavelength with the help of a birefringent tuning plate. The results showed that the cw lasing threshold was nearly constant from 820 to 920 nm, indicating that a

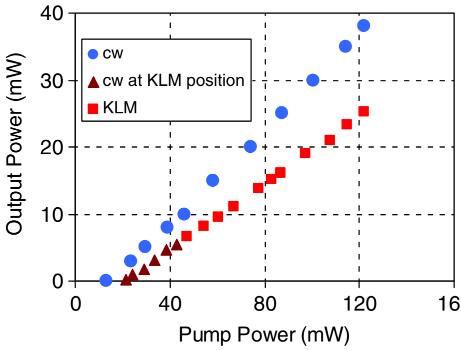

Fig. 3. Measured variation of the Cr:LiSAF laser output power as a function of the incident pump power.

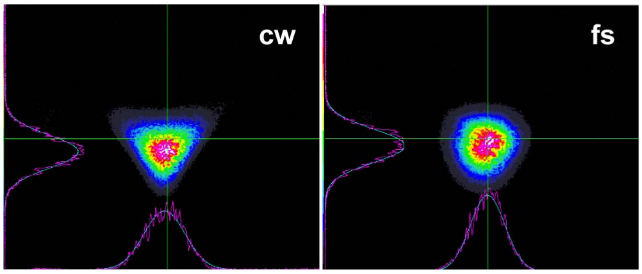

Fig. 4. Measured output beam profiles for cw and cw mode-locked (fs) cases. Measured M^2 values were around 1.25 and 1.1 for the cw and cw mode-locked cases, respectively.

constant gain profile is indeed obtained in this region with the help of the GMOC mirror.

Figure 3 also shows the efficiency curve taken at the mode-locking position. The location of the KLM operation point was around the center of the stability range (it was 1 mm away from the stability edge, and the width of the stability range was 2.5 mm). Since we did not operate near the stability edge, mode-matching between the cavity and pump modes remained relatively good, and the cw laser performance (cw at KLM position in Fig. 3) did not deteriorate by a noticeable amount. At the KLM position, the cw lasing threshold increased to only 20 mW, and the slope efficiency decreased to 26%. The Cr:LiSAF laser operated in only pure cw regime for pump powers up to around 45 mW, and, beyond that, stable KLM operation could be achieved. The corresponding intracavity laser power, required to sustain stable mode-locking was only 900 mW. We note that, even though we operated relatively far from the stability edge, the output beam profile of the cw laser at the mode-locked position was not symmetric (Fig. 4). We believe that the population lensing effect, described in [11], might be playing a role. Once mode locking is initiated, the laser output beam attained a symmetric beam profile and operated in the TEM_{00} mode. As a side note, a similar KLM operation point could be achieved also within the inner stability range.

As mentioned earlier, a fused silica prism pair with a separation of 30 cm was used for fine dispersion tuning of the cavity. This enabled tuning of the pulsewidth in the 13–50 fs range. Figure 5 summarizes the properties of the shortest pulses obtained from the Cr:LiSAF laser. The optical spectrum extends from 750 to 980 nm and is broad enough to support 11.8 fs pulses (calculated transform-limited pulsewidth). The minimum achievable time bandwidth product for this spectral shape is calculated to be 0.45. We have also calculated the autocorrelation deconvolution factor for this spectrum as 1.78. With these parameters, the measured pulsewidth was 13 fs, and the pulses were slightly chirped with a time-bandwidth product of 0.5. The average power of the pulses was measured as 25 mW at the incident pump power of 120 mW. This corresponds to a pulse energy of 200 pJ for the 126 MHz cavity. The peak power of the pulses was as high as 15 kW. The corresponding optical-to-optical and electrical-to-optical conversion efficiencies of the system were 21% and 7%, respectively. For the longer pulses (50 fs), average power as high as 40 mW, pulse energies as high as 320 pJ, and optical-to-optical conversion efficiencies above 30% could be achieved. Moreover, by inserting a vertical slit between the second prism and the flat high reflector, smooth tuning of the fs pulses could be achieved from 840 to 870 nm.

We note here that, in this setup, we could also initiate KLM with regular output couplers, with transmission ranging from 0.1% to 1%. However, compared to the GMOC, KLM operation was less stable, and pulse widths were limited to around 25 fs. When we increased the prism material insertion to obtain shorter pulses, KLM action disappeared and could not be initiated again. Moreover, the long-term stability and robustness of the KLM action was worse using regular output couplers. Looking at the literature, we actually see that, all the sub-20-fs results obtained with KLM Cr:LiSAF lasers used some kind of a hard aperture within the cavity (a slit or a knife edge) [4,9,12]. These results suggest that, with regular output couplers, soft-aperture KLM by itself is probably not sufficient in generating the required SAM to balance the strong gain filtering effect and sustain stable mode-locked operation (especially for sub-20-fs

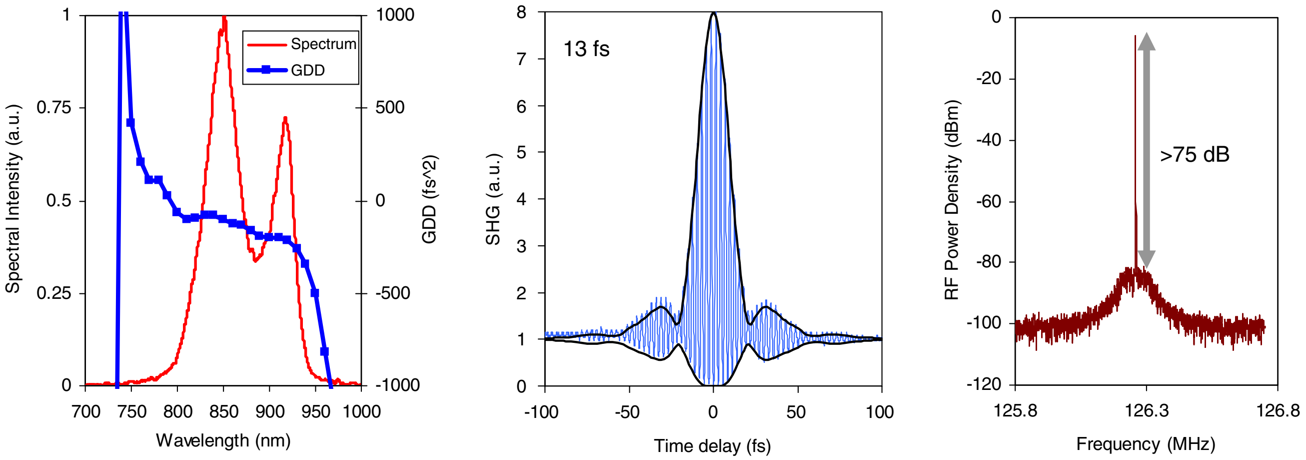

Fig. 5. Measured optical spectrum (left), calculated GDD profile of the cavity (left), interferometric autocorrelation (middle), and measured radio frequency spectrum (right) for the 13 fs long pulses with 25 mW average power and 126 MHz repetition rate. The data were taken at a pump power of 120 mW. The RF data were taken at 1 kHz resolution. In the middle graph, the solid curve is the envelope of the calculated autocorrelation by assuming a chirp-free pulse with the same spectral distribution.

pulses where the spectra become considerably broad). We have calculated that, with the GMOC, the effective output coupling decreases from 0.7% to 0.6%, when the laser switches from cw operation to KLM (calculated for the spectra of the 13 fs pulses). Hence, GMOC provides a 0.1% modulation depth (SAM), which improves the KLM stability and enables the generation of shorter pulses by balancing the gain filtering effect. This finding clearly demonstrates that GMOC technology enables robust KLM operation with long-term stability even in laser gain media with a low nonlinear refractive index.

As an additional advantage of GMOC, to obtain stable KLM, we did not need to operate the Cr:LiSAF laser near the edge of the stability region. Moreover, our KLM cavity did not require any hard apertures, which create additional loss. These properties enabled operation of the laser with higher efficiency. Hence, the optical-to-optical conversion efficiency (21% for 13 fs pulses and 30% for 50 fs pulses) that is achieved in this study is superior compared to earlier KLM Cr:LiSAF results in the literature (10 fs pulses with 0.27% efficiency in [9], 12 fs pulses with 0.76% efficiency in [4], 15 fs pulses with 3.8% efficiency in [12], 26 fs pulses with 0.78% efficiency in [13], 42 fs pulses with 5.25% efficiency in [2], 80 fs pulses with 11% efficiency in [14]).

As an alternative technology, direct-diode pumping of Ti:Sapphire with GaN diodes also has been demonstrated recently [15–18]. In initial studies, upon pumping with a single 1 W GaN diode at 450 nm ($M^2 \sim 1.5$), 114 fs long pulses with 13 mW average power have been obtained from a saturable Bragg reflector mode-locked Ti:Sapphire laser (1.3% efficiency) [15]. Later, 111 fs long pulses with 101 mW average power have been demonstrated at a pump power of 2 W (5% efficiency) [18]. Finally, 15 fs long pulses with 30 mW average power have been obtained in a KLM Ti:Sapphire laser, using a pair of 1.2 W diodes as the pump source (1.25% efficiency) [17]. We believe that the efficiencies from the diode-pumped KLM Ti:Sapphire laser systems also could be improved by using the GMOC technology. However, we note here that the figure of merit of Cr:LiSAF crystals is about an order of magnitude better compared to Ti:Sapphire [8]. Moreover, an additional parasitic loss of about 1% was reported in Ti:Sapphire when pumped at shorter wavelengths [15,18]. In short, the superior quality of Cr:LiSAF crystals enables the construction of a KLM system with pump powers of only around 100 mW as shown in this study, which is not possible in Ti:Sapphire due to the above-mentioned problems. Hence we believe that Cr:LiSAF systems still possess advantages compared to Ti:Sapphire in terms of pump power requirements and efficiency.

In conclusion, we have employed a GMOC to demonstrate robust and efficient KLM operation of a diode-pumped, low-cost Cr:LiSAF laser with long-term stability. An electrical-to-optical conversion efficiency of around 7% was attained, which is around two orders of magnitude better than what is achievable with today's commercial Ti:Sapphire systems. We believe that, with future progress, low-cost, compact, and efficient KLM Cr:LiSAF lasers with GMOC technology have the potential to serve as attractive laser sources for many scientific and technological applications.

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