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We describe a diode-pumped Kerr-lens mode-locked Cr^{3+}:$LiSrAlF_6$ laser that produces 50 mW of 70-fs pulses in the 820–890-nm range when pumped by two red diodes of 400 mW each. By using a lower-transmission output coupler we have demonstrated for the first time to our knowledge a self-starting regime with an output power of 10 mW and 55-fs pulses.

The domain of ultrashort lasers has been revolutionized in the past few years by the demonstration of self-mode locking by Spence *et al.*[1] in an Ar-ion-pumped Ti:sapphire laser that yielded femtosecond pulses. Although this technique was first demonstrated in Ti:sapphire, it has recently been extended to other solid-state laser materials such as Nd:YLF,[2] Cr^{4+}:YAG,[3] Cr^{4+}:fosterite,[4] and Pr^{3+}:YLF.[5] In searching for a compact all-solid-state femtosecond source researchers have developed a Ti:sapphire femtosecond laser pumped by a cw intracavity frequency-doubled diode-pumped Nd:YLF laser.[6] However, this solution still remains complex and is actually not really promising. Cr^{3+}:$LiSrAlF_6$ (Cr:LiSAF) is an attractive alternative because of its absorption band, which is shifted to the red compared with Ti:sapphire. This feature permits the use of high-power red laser diodes as pumping sources. However, obtaining short pulses with good average power is a challenge in diode-pumped Cr:LiSAF because of its low small-signal gain compared with that of other materials such as Nd:YAG or Nd:YLF. In the past year progress has been reported in this area. Nevertheless, the process of Kerr-lens mode locking (KLM), which always governs the production of ultrashort pulses in these lasers, is generally not self-starting, and initiating and enhancing the pulse formation always requires some additional amplitude modulation. This can be accomplished with a multiple-quantum-well or antiresonant Fabry–Perot saturable absorber[7,8] and regenerative mode locking.[9]

In this Letter we report on a Kerr-lens mode-locked diode-pumped Cr:LiSAF laser that starts with a simple moving mirror and produces 70-fs pulses at 850 nm with an average power of 50 mW. Furthermore, by using a lower-transmission output power and thus increasing the intracavity power we were able to obtain what is to our knowledge the first self-starting behavior in this kind of femtosecond diode-pumped laser.

The Cr:LiSAF crystal[10] from Lightning Optical Corporation was doped with a Cr^{3+} concentration of 1.5% by weight, and the absorption was 95% of the pump power. The crystal was Brewster–Brewster cut, and the central path was 5 mm. To pump this Cr:LiSAF crystal, we used two single-stripe GaAlInP laser diodes with an emitting wavelength of 670 nm. These diodes are produced by Applied Optronics. The output power was 400 mW for a driving current of 0.8 A and an emitting area of 100 μm × 1 μm. The relatively good beam quality permitted us to pump the amplifying crystal through a cavity mirror and to use a classical X-fold cavity configuration, as shown in Fig. 1. We were also able to use a lower-doped crystal (1.5%) than in our previous studies,[11] thereby reducing the thermal effects that occur in the crystal.

KLM is a nonlinear process that depends strongly on the intracavity power density, so the spot size inside the crystal has to be as small as possible. For this reason it is necessary to reshape the beam coming from the diode so as to maintain a good overlap between the pump beam and the small cavity mode. A first objective (f = 15 mm; numerical aperture, 0.6) collimated the diode beam. Then a cylindrical afocal system with a magnification of 10 modified the beam in the direction parallel to the junction of the diode. Finally, to focus the diode through the cavity mirror, we used an objective with a long focal length (f = 100 mm, doublet). Taking into account the transmission of the reshaping optics, the total absorbed pump power was 300 mW for each pump direction. With a CCD camera we measured a pumping spot size of approximately 60 μm × 30 μm. First, we tested the pumping scheme efficiency by operating the laser in the cw regime with a simple four-mirror astigmatically compensated (folded angle, 14°) X-fold cavity (Fig. 1). The Cr:LiSAF crystal was placed at the fo-

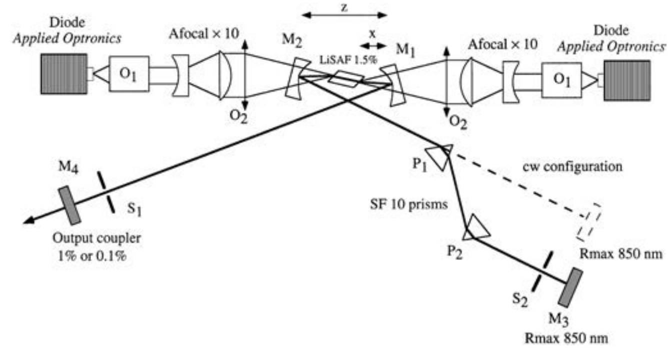

Fig. 1. Schematic of the laser cavity. M_1–M_4, mirrors; S_1–S_2, slits; P_1–P_2, prisms; O_1, O_2, objectives.

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cus point of two concave mirrors, M_1 and M_2, that have a radius of curvature of 100 mm and are high-reflection coated between 800 and 900 nm with high transmission at 670 nm. The cavity ended with plane mirror M_3 (Rmax) and output coupler M_4 (transmission, 1%). In this configuration we obtained 150 mW of cw output power at 850 nm for an absorbed pump power of 600 mW and a threshold of 80 mW. This corresponded to a slope efficiency of ~30%. No thermal effect was observed in the Cr:LiSAF crystal, and the beam mode was perfectly TEM_{00}. By inserting a Lyot filter in the cavity we achieved a tunability of 100 nm, limited in the infrared by the dielectric coating of the cavity mirrors.

To obtain femtosecond pulses, we first added two SF10 prisms with a tip-to-tip distance of 250 mm to compensate for the group-velocity dispersion in the cavity. In this case the maximum output power decreased to 100 mW owing to losses (scattering) in the prisms. Highly reflective mirror M_3 was mounted on a shaker to initiate the KLM regime. To enhance the discrimination between the cw and mode-locked regimes, we followed the previous experiments of Cerullo *et al.*[12] that indicated the best cavity configuration; i.e., the two collimated arms were set to the same length (750 mm), and we carefully adjusted the folding mirror distance z and the position x of the Cr:LiSAF crystal (Fig. 1). In the optimized cavity for pulsed operation, x was set to ~51.5-mm and z to ~104 mm. Two slits were placed in the sagittal plane of the cavity. To enhance and stabilize the pulsed regime, we placed slit S_1 near the output coupler. It acted as a hard aperture, which leads to higher losses in the cw regime than in the Kerr-lens mode-locked regime. In fact, when the laser was optimized for the pulsed regime, the cw output beam mode was multimode. By adjusting the width of the slit we were able to initiate the femtosecond regime, and in this case the beam mode became TEM_{00}. The second slit, S_2, was placed in the dispersive arm after the prisms and was used to tune and control the emitting wavelength. We first used a cw Kr-ion laser as the pump source to optimize the cavity configuration in the pulsed regime and to decrease the pumping threshold for mode-locked operation. When ultrashort pulses were obtained for typically 300–400 mW of pump power, we removed the Kr-ion pump beam and inserted the diode pumping lines.

In this case and with a 1% output coupler we obtained 13 mW of sub-100-fs pulses with only one pumping diode. We initiated the regime by moving the end cavity mirror or by slightly tapping one of the mirrors. By adding the second diode we demonstrated pulses of 70 fs, assuming a sech^2 pulse shape for an output power of 50 mW and an absorbed pump power of 600 mW. Figure 2(a) shows a background-free autocorrelation trace of the laser pulses obtained at 850 nm. Figure 2(b) is a spectrum corresponding to these pulses and shows a FWHM intensity of 11.7 nm, indicating a time–bandwidth product $\Delta t \Delta \nu$ of 0.34. This value is very close to the limit for transform-limited pulses, which is 0.315. To compensate for the positive group-velocity dispersion introduced by the output coupler (8 mm thick) and the autocorrelator elements (focusing lens and beam splitter), we added an external sequence of four prisms (prism separation, 30 cm) between the laser and the autocorrelator.

These results are comparable with those obtained with other techniques,[8,9] but we believe it is the first time that a simple starting mechanism has been used in such a diode-pumped Cr:LiSAF laser. Once KLM was initiated, the moving mirror could be stopped, and the self-mode locking continued for several hours without any adjustments of the cavity. As a result of diode-pumping, the pulse-to-pulse stability was very good; we measured amplitude fluctuations on a millisecond time scale of less than 1%. By translating slit S_2 in the sagittal plane we achieved tunability between 820 and 890 nm with no change in the duration of the pulses.

To attain a truly self-starting regime, we replaced the output coupler by a highly reflective mirror. In this configuration, because of a higher intracavity power, we achieved self-starting KLM without the need for the shaking mirror. To study the starting mechanism, we first blocked the cavity over a period of several seconds, and then we unblocked the laser. Typical behavior of the laser is shown in Fig. 3. After 1 s of cw emission the laser became unstable and changed to the femtosecond regime. When the cavity was blocked over a shorter period (typically less than 1 s), the buildup time was reduced to ~200 μs. A self-sustaining femtosecond regime over several hours of operation was obtained. Pulses as short as 55 fs (assuming a sech^2 pulse shape) at 850 nm with an average output power of 10 mW were produced with a corresponding spectrum of 16.7 nm (Fig. 4). The

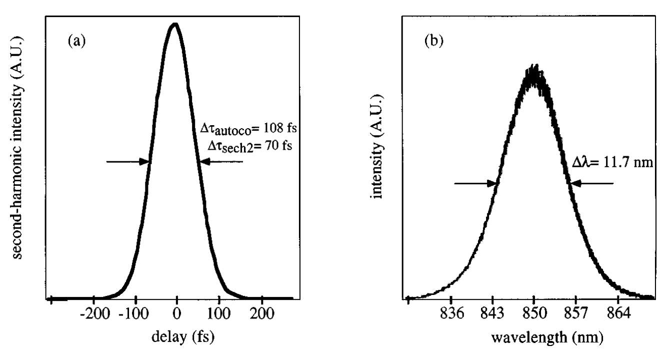

Fig. 2. (a) Autocorrelation trace and (b) spectrum of the self-mode-locked Cr:LiSAF laser.

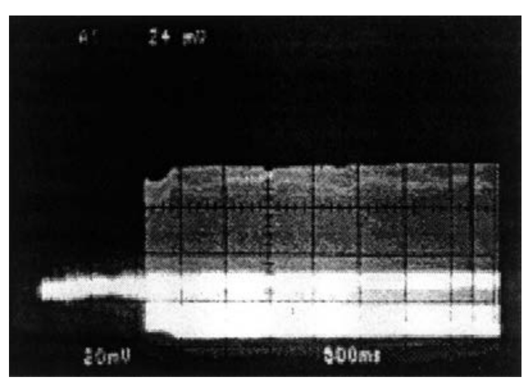

Fig. 3. Self-starting behavior of the laser. The laser cavity is blocked for a few seconds and then unblocked (start of the trace). The scale is 500 ms/division.

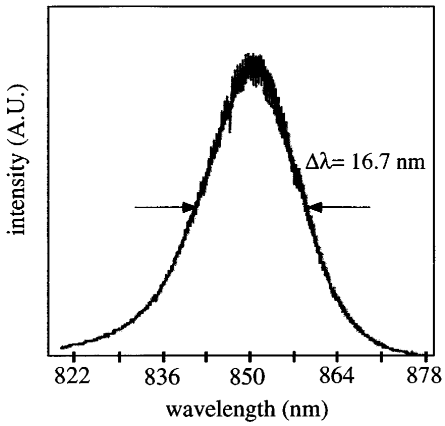

Fig. 4. Spectrum of the self-starting laser's 55-fs pulses.

time–bandwidth product was 0.38, indicating that the pulses were not transform limited. This can be explained by the asymmetry of the pulse spectra (Fig. 4), which could be due to third-order dispersion.

Further improvements could be made by use of two LaK31 prisms instead of high-order-dispersion SF10 prisms, thereby producing shorter pulses. It has been demonstrated that the use of such prisms permits the production of pulses shorter than 30 fs.[9] We also plan to replace the Cr:LiSAF crystal with a Cr:LiSGaF crystal that exhibits similar spectroscopic features but lower passive and scattering losses and significantly lower thermal expansion and anisotropy, which makes thermal lensing and cracking less of a problem and yields higher efficiency.

In conclusion, we have reported on a simple and compact diode-pumped femtosecond Kerr-lens mode-locked Cr:LiSAF laser. By using a moving mirror to start the KLM regime and a 1%-transmission output coupler we have obtained 50 mW of 70-fs pulses at 850 nm. With a highly reflective mirror we have demonstrated for the first time to our knowledge a self-starting diode-pumped Cr:LiSAF laser that delivers pulses of 55 fs with an average output power of 10 mW. We believe that this kind of compact and simple source will have many applications. For example, it can be the master oscillator for a powerful amplified femtosecond source based on a Ti:sapphire regenerative amplifier. On the other hand, by using a diode-pumped Cr:LiSAF regenerative amplifier[13,14] we could obtain an all-solid-state source producing microjoule femtosecond pulses. Such a source could be useful for medical applications such as fluorescence microscopy.

Note added in proof: By adding two LaK31 prisms in the cavity instead of SF10 prisms we have obtained transform-limited pulses of 45 fs with an average output power of 30 mW.

References

1. D. E. Spence, P. N. Kean, and W. Sibbett, Opt. Lett. **16,** 42 (1991).
2. G. P. A. Malcolm and A. J. Ferguson, Opt. Lett. **16,** 1967 (1991).
3. A. Sennaroglu, C. R. Pollack, and H. Nathel, in *Advanced Solid-State Lasers*, T. Y. Fan and B. H. T. Chai, eds., Vol. 20 of OSA Proceedings Series (Optical Society of America, Washington, D.C., 1994), pp. 228–231.
4. V. Yanovsky, Y. Pang, F. Wise, and B. I. Minkov, Opt. Lett. **18,** 1541 (1993).
5. S. Ruan, J. M. Sutherland, P. M. W. French, J. R. Taylor, and B. H. T. Chai, in *Digest of Meeting on Advanced Solid-State Lasers* (Optical Society of America, Washington, D.C., 1995), pp. 122–124.
6. K. Lamb, D. E. Spence, J. Hong, C. Yelland, and W. Sibbett, in *Conference on Lasers and Electro-Optics*, Vol. 8 of 1994 OSA Technical Digest Series (Optical Society of America, Washington, D.C., 1994), paper CWI3.
7. P. M. W. French, R. Mellish, J. R. Taylor, P. J. Delfeytt, and L. T. Florez, Electron. Lett. **29,** 1262 (1993).
8. D. Kopf, K. J. Weingarten, L. R. Brovelli, M. Kamp, and U. Keller, Opt. Lett. **19,** 2143 (1994).
9. M. J. P. Dymott and A. I. Ferguson, Opt. Lett. **19,** 1988 (1994).
10. S. A. Payne, L. L. Chase, L. K. Smith, W. L. Kway, and H. W. Newkirk, J. Appl. Phys. **66,** 1051 (1989).
11. F. Falcoz, F. Balembois, P. Georges, and A. Brun, Opt. Lett. **20,** 1274 (1995).
12. G. Cerullo, S. De Silvestri, and V. Magni, Opt. Lett. **19,** 1040 (1994).
13. F. Balembois, P. Georges, F. Salin, and A. Brun, Opt. Lett. **18,** 1250 (1993).
14. S. C. W. Hyde, N. P. Barry, R. Mellish, P. M. W. French, J. R. Taylor, C. J. van der Poel, and A. Valster, Opt. Lett. **20,** 160 (1995).