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Self-starting self mode-locked femtosecond diode pumped Cr:LiSAF laser

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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 $\sim 30\%$. 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

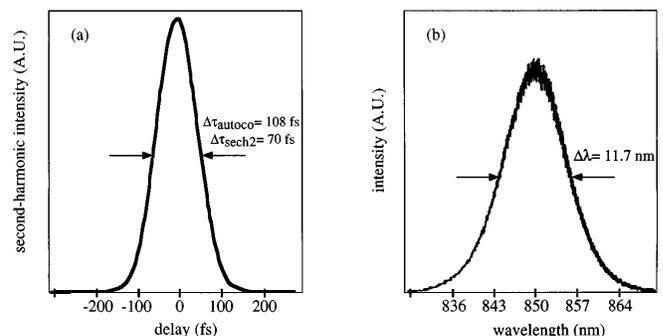


Fig. 2. (a) Autocorrelation trace and (b) spectrum of the self-mode-locked Cr:LiSAF laser.

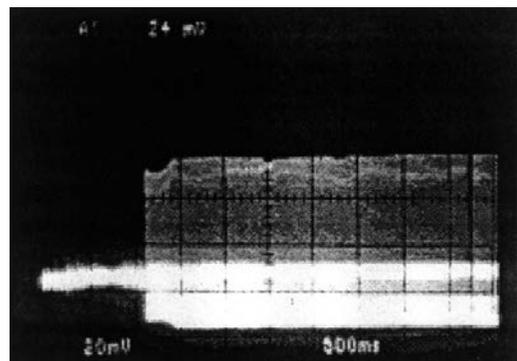


Fig. 3. Self-starting behavior of the laser. The laser cavity is blocked for a few seconds and then unblocked (start of the trace). The scale is 500 ms/division.

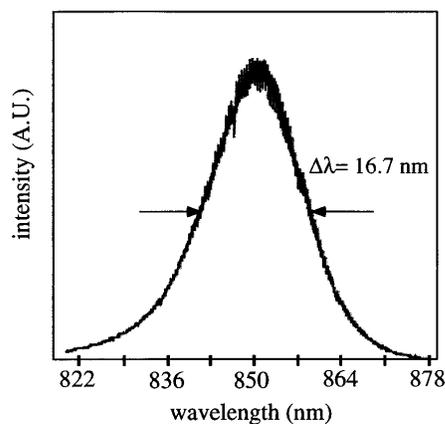


Fig. 4. Spectrum of the self-starting laser's 55-fs pulses.

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 re-

generative 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.

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