Prismless passively mode-locked femtosecond Cr:LiSGaF laser

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A Kerr-lens mode-locked Cr:LiSrGaF laser containing no intracavity prisms has been demonstrated for the first time to the authors' knowledge. The laser produced stable near-transform-limited 44-fs pulses with an output power of 200 mW, tunable between 833 and 857 nm. Low-loss Gires–Tournois structured dielectric mirrors were used for dispersion control. The measured group-delay dispersion of the active medium as well as of the mirrors permitted to minimize the number of reflections, permitting higher output power.

Recent years have been marked by impressive developments in the field of ultrafast-pulse lasers: the discovery of Kerr-lens mode locking (KLM) in Ti:sapphire[1] and subsequent maturing of the Ti:sapphire-based ultrashort-pulsed technology down to sub-10-fs pulses.[2] Currently the KLM Ti:sapphire laser is a widely used commercially available tool. However, the bulky and expensive high-power cw lasers usually required for its pumping remain the major limitation to the development of large-scale real-world applications of ultrashort pulses. Therefore there is a strong impetus in femtosecond technology research toward developing compact, stable, and less expensive ultrafast sources. Especially attractive for this purpose are Cr^{3+}-doped $LiSrAlF_6$ (Cr:LiSAF; Refs. 3–5) and $LiSrGaF_6$ (Cr:LiSGaF; Refs. 6–8) which provide broadband gain over a spectral region similar to that of Ti:sapphire and suitable for AlGaInP laser diode pumping. A KLM Cr:LiSAF laser produced pulses as short at 18 fs,[9] whereas the Cr:LiSGaF laser has the advantage of substantially higher achievable output powers.[6,8] Recently a novel mirror dispersion control approach was suggested and successfully realized in a Ti:sapphire laser,[10,11] allowing stable, sub-10-fs pulses to be produced from a prismless Ar^+-pumped oscillator.[2] The first prismless diode-pumped Cr:LiSAF laser based on a semiconductor saturable-absorber mirror (no KLM action) with Gires–Tournois (GT) coating was realized last year by Kopf *et al.*[5] and yielded 160-fs pulses at 25-mW output power.

We report what is to our knowledge the first prismless Kr^+-pumped KLM Cr:LiSGaF laser, with low-loss GT structured dielectric mirrors replacing conventional cavity mirrors. The laser produced stable, reproducible, near-transform-limited 44-fs pulses at 200 mW of average output power.

The first suggestions for the compression of chirped optical pulses by means of interferometerlike structures go back to 1964.[12,13] Based on this idea, the technology of dispersive dielectrical mirrors was developed recently.

Currently there exist two types of dispersive mirror: GT interferometers,[14,15] which are essentially étalons, and chirped dielectric mirrors.[10] Chirped mirrors exhibit nearly constant group-delay dispersion (GDD) over a much larger bandwidth than can be obtained by GT interferometers for dispersion control. GT mirrors have the advantage of negligible transmission loss and relatively high and adjustable (by means of a change of the angle of incidence) GDD.

We performed lasing experiments with both chirped and GT mirrors. The results indicate that at the present state of research high losses in the chirped mirrors do not permit their use for dispersion control in Cr:LiSGaF- or Cr:LiSAF-based oscillators, unlike Ti:sapphire, which tolerates significantly higher intracavity losses.

The losses in dielectric mirrors originate from scattering and absorption inside the dielectric layers.[16] Dispersive mirrors, however, exhibit higher losses than conventional quarter-wave mirrors because of the higher field concentration within the layers (field trapping in interferometric GT structures and higher penetration depth in chirped mirrors).

Briefly, a GT dielectric mirror consists of a top reflector, a spacer region, and a practically 100% bottom reflector. In Fig. 1 we compare the group delay

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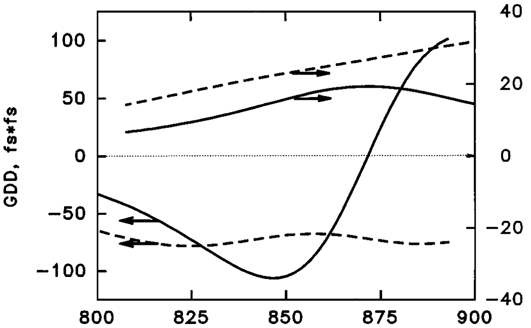

Fig. 1. Comparison of GDD and group delay per reflection of GT mirrors (solid curves) and chirped mirrors (dashed curves).

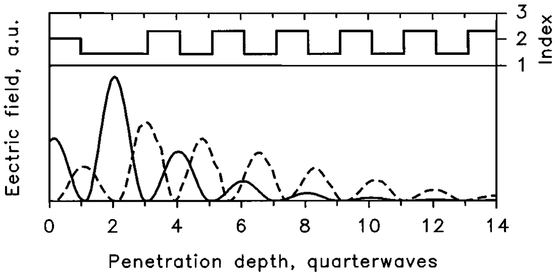

Fig. 2. Comparison of electrical field distribution within a GT mirror (solid curve) and a chirped mirror (dashed curve). The inset shows the index-of-refraction change within the GT structure.

per reflection and GDD of a chirped mirror and a GT interferometer, both designed for 850 nm as a central wavelength. It is easily seen that the GDD of the GT structure is greater than that of the chirped mirror over a certain bandwidth, permitting a smaller number of reflections. We achieve this by increasing the GDD by using a high-index top layer at the expense of reduced bandwidth. Furthermore, the chirped mirror exhibits ~50% higher group delay per reflection. Because the losses in the layers are proportional to the group delay per reflection,[16] we expect significant reduction of intracavity losses when using GT-type mirrors.

An additional advantage of GT structures with respect to losses is the fact that the electric field can be effectively concentrated in the low-refractive-index material placed in the spacer region (Fig. 2), which has fewer losses than high-index materials. In most of our experiments we used TiO_2 ($n = 2.31$) and SiO_2 ($n = 1.45$) as high- and low-index materials, respectively.

The dispersion of the GT mirrors was measured by the spectrally resolved white-light interferometer technique described in Ref. 17. We found, however, that this method cannot easily be applied to measuring the dispersion of the laser-active medium because the plane-wave approximation that we had used is no longer valid, mainly because of the relatively poor flatness of the crystal sample surface used. Therefore we adopted the measurement arrangement of Sainz *et al.*[18] and Kumar and Rao,[19] which requires practically the same measurement apparatus but is insensitive to the problems mentioned above.

We experimentally verified the reliability of our dispersion measurement on the crystal by measuring the dispersion of the GT mirrors, using both Sainz's[18] and Bor's[17] arrangements. The measured GD and GDD values were the same within the error bar of the data obtained by the former arrangement. The measured dispersion of a Brewster-cut Cr:LiSGaF crystal is shown in Fig. 3 (measured $E||c$). The details of this dispersion measurement of the LiSGaF crystal as well as of some other laser-active crystals such as LiSAF and LiCAF will be published elsewhere.[20]

In our laser experiments we used an astigmatically compensated X-folded cavity with a 6-mm Cr:LiSGaF crystal (0.75% Cr^{3+}, absorption length 4.7 mm) placed between two concave mirrors with radii of curvature of 100 mm.[21] Mirror R_1 (Fig. 4) had a dichroic dielectric coating to permit pumping with the 647- and 676-nm lines of a Kr^+-ion laser. A 2.3% output coupler was used. The design parameters and performance of this laser containing the prism pair were described in Ref. 8.

As a first step, we replaced the prism pair with a multiple-reflection GT mirror pair so that the calculated amount of GDD was not less than that of the prism pair. This required 12 reflections of $\simeq -50\ fs^2$/bounce. The laser could be mode locked, achieving $\simeq$50-fs pulse duration, at typically 0.95–1.15 W of absorbed power. However, the high number of GT reflections introduced appreciable losses into the cavity, so the maximum output power was limited to 100 mW. Inasmuch as we measured the transmission through the GT mirrors to be below 0.01%, less than that of our conventional high reflector ($\simeq$ 0.02%), we attribute the additional losses ($\simeq$ 0.1%/bounce) to scattering, as described above.

We therefore attempted to reduce the number of reflections to a minimum, combining GT mirrors produced with different technology and nominal GDD. Our final design is shown in Fig. 4, and it incorporates three GT mirrors, one of them being curved.

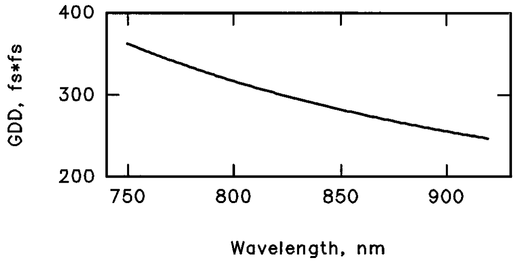

Fig. 3. GDD/cm of a Cr^{3+}:LiSGaF crystal.

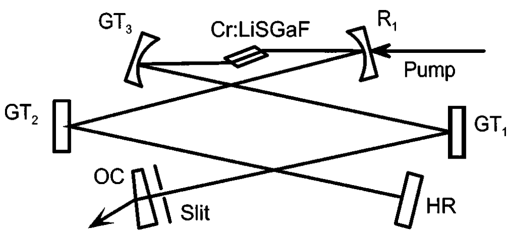

Fig. 4. Schematic of the KLM Cr:LiSGaF laser with GT mirrors replacing resonator mirrors: OC, output coupler; GT's, GT mirrors; HR, high reflector.

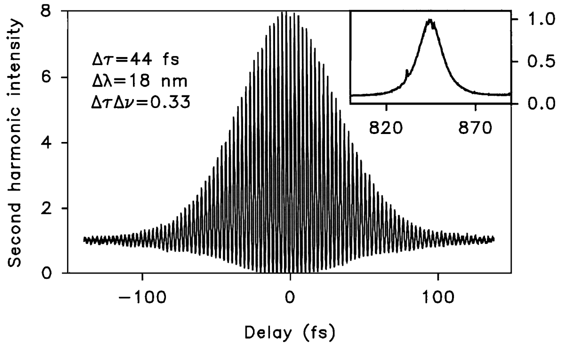

Fig. 5. Autocorrelation trace of a mode-locked Cr:LiSGaF laser. The inset shows the output spectrum.

This design is characterized by its compactness and excellent long-term alignment stability. With this laser we routinely reproduced mode-locked operation at pump powers of 1.5–1.8 W (0.95–1.15 W absorbed in the crystal) and mode-locked output powers of 150–200 mW. Pulse durations were typically 45–50 fs, with the shortest measured pulse duration of 44 fs (Fig. 5). The pulses were near transform limited, with a time–bandwidth product $\Delta\nu\Delta\tau \simeq 0.33$–$0.36$. By varying the angles of incidence at the flat GT mirrors between 5° and 30° and choosing different GT mirror combinations it was possible to tune the central wavelength between 833 and 857 nm. Tilting the GT mirrors shifts the maximum GDD toward shorter wavelengths, and the laser is forced to operate at the shifted wavelength. However, the shortest pulses were measured at $\lambda = 842$ nm, which is close to the maximum of the fluorescence band. With the repetition rate approximately 80 MHz, the output and intracavity pulse energies were found to be 2.5 and 110 nJ, respectively.

We also found that increasing the intracavity pulse energy above 100–110 nJ was often accompanied by a reproducible double-pulse oscillation regime, with a typical pulse separation of 300–500 fs. Both pulses appeared to be more or less identical, and the separation was stable over an indefinite time. To suppress the double-pulse regime it was necessary to increase the self-amplitude modulation further, eventually bringing the intracavity pulse energy below 100 nJ (output power $\simeq$190 mW).

As was described in Ref. 21, enhanced dispersive wave generation was observed under certain conditions and with particular GT mirror combinations when the laser operated in the vicinity of zero net intracavity GDD and considerable high-order dispersion.[22] This suggests that high-order dispersion, which is intrinsic to interferometer-type structures, is likely to be a significant limiting factor in the operation and propagation of the pulses and must be carefully compensated for.

In conclusion, we have demonstrated a compact and robust Kerr-lens mode-locked Kr^+-pumped Cr:LiSGaF laser, producing powerful (200-mW average power) femtosecond (44-fs) pulses without the use of prisms. We achieved dispersion compensation by replacing conventional mirrors with the low-loss GT structured dielectric mirrors. The implementation of diode lasers for pumping will likely be the final step in the development of a powerful compact ultrashort-pulse source.

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