Generation of 20-fs pulses by a prismless Cr^{4+}:YAG laser

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Ultrafast optical pulses shorter than 20 fs with 400-mW average power at a 110-MHz repetition rate have been generated by a Cr^{4+}:YAG laser with only double-chirped mirrors for dispersion compensation. The corresponding pulse spectrum has a peak intensity at 1450 nm and extends from 1310 to 1500 nm full width at half-maximum (FWHM). These pulses, which are believed to be the shortest generated to date from a Cr^{4+}:YAG laser, are only four optical cycles within the FWHM intensity width.

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Mode-locked solid-state lasers are capable of generating ultrashort optical pulses with broad spectra and high peak intensities. Cr^{4+}:YAG lasers have the ability to produce such pulses in the wavelength range from 1300 to 1600 nm.[1–3] These lasers operate at room temperature, do not require a vacuum, and have larger gain bandwidths than Er-doped fiber lasers.[4] In previous work, Tong *et al.*[5] generated 43-fs pulses using a hard-aperture Kerr-lens mode-locked Cr^{4+}:YAG laser with fused-silica prisms for dispersion compensation. The minimum pulse width in this laser was reported to be limited by third-order dispersion (TOD).[6] Other groups have reported self-starting[7–9] or high-repetition-rate[10–12] mode-locked Cr^{4+}:YAG lasers.

To generate shorter optical pulses, one must control chromatic dispersion within the laser cavity over a large wavelength range. In standard mode-locked laser cavities, geometric and material dispersion from prism pairs compensate for group-delay dispersion (GDD) of the laser gain media but often limit the minimum achievable pulse width by introducing higher-order dispersion. As an alternative to prisms, chirped mirrors have been developed both to compensate for higher-order dispersion and to provide a large mirror bandwidth.[13] More recently, double-chirped mirrors (DCMs) have been introduced to reduce residual oscillations in the dispersion of chirped mirrors caused by spurious reflections within the mirror as a result of improper impedance matching of the incident optical wave.[14] DCMs have been used for intracavity dispersion compensation to generate two-cycle optical pulses from Ti:sapphire lasers with a pulse width of 5 fs at 800 nm,[15,16] and three-cycle pulses with 14-fs duration at 1300 nm from Cr:fosterite.[17]

For the work reported here, DCMs were used for broadband higher-order dispersion compensation of a Cr^{4+}:YAG laser. Pulses shorter than 20 fs were measured directly from the prismless laser. The pulse spectrum peaked at 1450 nm and ranged from 1310 to 1500 nm at half-maximum. On a logarithmic scale, spectra from 1140 to >1700 nm, the limit of our optical spectrum analyzer, were observed.

A schematic of the Z-fold laser cavity is shown in Fig. 1. The laser crystal is a 2-cm-long, 3-mm-diameter Brewster–Brewster-cut rod, supplied by A. V. Shestakov of E. L. S. Company. Pump light at 1064 nm from a Spectra-Physics 11-W Nd:YVO_4 laser is focused by a 10-cm focal-length lens into the crystal. The laser crystal has a linear absorption of 1.5 cm^{-1} and is cooled to 13 °C during operation. Surrounding the laser crystal are two 10-cm radius-of-curvature DCMs (M1 and M2), rotated 16° from normal incidence for astigmatism compensation. One arm of the laser is 70 cm long and contains both an additional DCM (M3) and an unchirped quarter-wave-stack high reflector (M4). The second arm of the laser is 50 cm long and contains a broadband output coupler with a minimum transmission of 0.7% at 1515 nm and less than 1.4% transmission from 1420 to 1630 nm. The lasing threshold is at 0.7 W of absorbed pump power, and the cw output power is 1 W for 9 W of absorbed pump.

DCMs, composed of 48 layers of SiO_2 and TiO_2, were designed to compensate for the dispersion of a Cr^{4+}:YAG crystal and grown by use of a

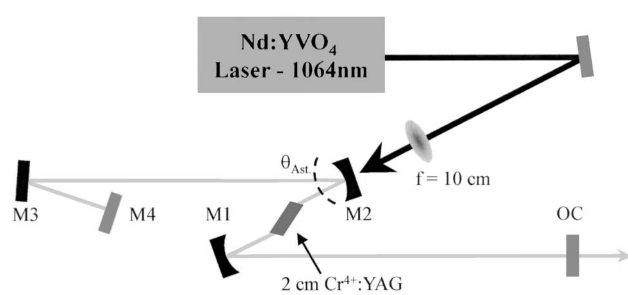

Fig. 1. Schematic of the Cr^{4+}:YAG laser cavity: Mirrors M1–M3 are DCMs, M4 is a quarter-wave-stack high reflector, and OC is an output coupler.

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state-of-the-art ion-beam sputtering technique.[18] The GDD of Cr^{4+}:YAG,[19] of a DCM (both design and measurement), and of the full laser cavity are all shown in Fig. 2. The 2-cm (4-cm round-trip) Cr^{4+}:YAG crystal has a GDD of 450 fs^2 and third-order dispersion of 6000 fs^3 at 1500 nm and zero GDD at 1590 nm. the DCMs were measured with a white-light interferometer technique[20] to have a roughly linear anomalous dispersion from 1325 to 1575 nm, a GDD value of ~ -125 fs^2, and a TOD of ~ -1000 fs^3 at 1500 nm for reflection at normal incidence. A dispersion-compensated cavity was created by use of six DCM reflections within each cavity round trip to compensate for the Cr^{4+}:YAG crystal. Effects of the broadband output coupler and the unchirped high reflector are both included in the net cavity dispersion plot in Fig. 2. Oscillations in the GDD of the laser cavity are due to residual spurious reflections caused by imperfect impedance tapering of the DCM. Because the DCMs were designed for normal incidence, these GDD oscillations were enhanced as a result of the large angle of incidence. The GDD calculated for off-normal DCM reflection was included in the net cavity dispersion.

We mode locked the laser by first aligning it for optimal cw power. The curved mirror separation and crystal position were then varied until Kerr-lens mode locking was observed. We initiated mode locking by tapping one of the end mirrors. The average power of the 110-MHz pulse train was 200 to 400 mW, depending on the alignment, for 9 W of absorbed pump. Water vapor in air introduces intracavity GDD and loss through a series of absorption lines from 1300 to 1500 nm.[21] To remove this water vapor, we enclosed the optical path and purged it with dry nitrogen gas. An example of the mode-locked pulse spectrum, measured with a calibrated optical spectrum analyzer, is shown on both linear and log scales in Fig. 3. Significant spectrum is present above the noise floor within the wavelength range from 1140 to >1700 nm (the optical spectrum analyzer used has a long-wavelength limit of 1700 nm) and has a full width at half-maximum (FWHM) of 190 nm, from 1310 to 1500 nm. The spectrum is smooth, with a relatively flat top from 1340 to 1470 nm. The output coupler, which rolls off significantly at wavelengths smaller than 1350 nm, enhances the output spectrum at shorter wavelengths.

The pulse width was measured by fringe-resolved autocorrelation. The beam was split and recombined by broadband metallic beam splitters and focused by an off-axis parabolic mirror onto a silicon p–i–n photodiode to perform the autocorrelation function by two-photon absorption. An autocorrelation trace is shown in Fig. 4. The abscissa was calibrated by the interference fringes of a He–Ne laser. Chirp from the dispersion of extracavity optical elements was compensated for by two BaF_2 prisms and one DCM bounce. The pulse width is estimated to be 18.3 fs for sech-shaped and 17.0 fs for Gaussian-shaped pulses. We used a pulse-retrieval algorithm[22] to reconstruct the pulse profile by fitting the measured interferometric autocorrelation with an autocorrelation function calculated from the experimentally retrieved spectrum and a varying phase profile. The retrieved pulse-intensity envelope has a width of 19.5 fs. A Fourier transform of the optical spectrum, assuming a flat phase profile, indicates a bandwidth-limited pulse width of 17.5 fs.

The prismless cavity reported here consists only of DCMs for dispersion compensation. Prisms add additional loss, which can be detrimental to the output power of loss-sensitive Cr^{4+}:YAG lasers and complicates laser alignment. In addition, many glass prisms have been found to contain traces of water that add intracavity absorption, leading to thermal effects due to glass heating. Because the cavity is prismless, however, it is not possible to fine tune the dispersion of the cavity to optimize mode locking. The pulse width might be shortened by use of prism pairs to fine tune the intracavity dispersion. Prism-based cavity designs may also allow expansion of the dispersion-compensation wavelength range.

In conclusion, an ultrafast Cr^{4+}:YAG laser has been built with only DCMs for dispersion compensation. Pulses shorter than 20 fs have been measured by interferometric autocorrelation. The corresponding

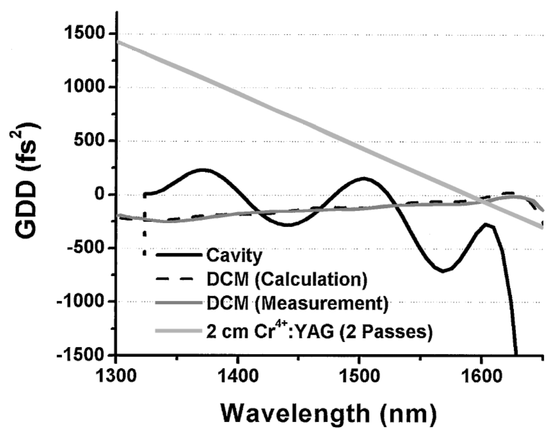

Fig. 2. GDD of two passes through a 2-cm Cr^{4+}:YAG crystal, and a single DCM, and the sum of all optical elements in the laser cavity. The net cavity GDD curve includes six reflections from DCMs, a single unchirped quarter-wave-stack high reflector, and an output coupler.

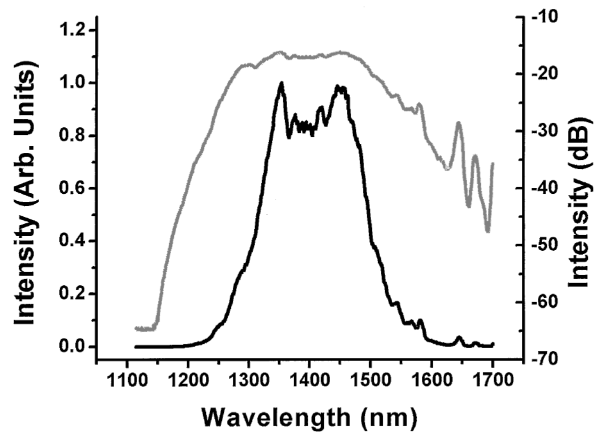

Fig. 3. Optical power spectrum of a Cr^{4+}:YAG pulse. The darker curve corresponds to a linear scale (left-hand axis) and the lighter curve corresponds to a logarithmic scale (right-hand axis). The FWHM is 190 nm, with a peak at 1450 nm.

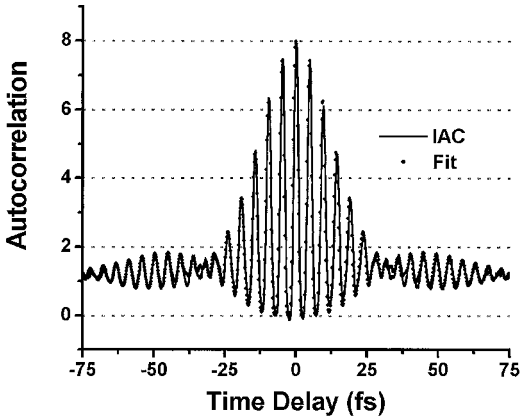

Fig. 4. Measured autocorrelation function from an interferometric two-photon absorption autocorrelator (IAC) and fit by a pulse-retrieval algorithm. A pulse width of 19.5 fs is calculated by the pulse-retrieval algorithm, 18.3 fs by assumption of sech-shaped pulses, and 17.0 fs by assumption of Gaussian-shaped pulses.

pulse spectrum is centered at 1460 nm and spans 1310 to 1500 nm at FWHM.

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