Generation of 11-fs pulses from a Ti:sapphire laser without the use of prisms

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The generation of highly stable optical pulses as short as 11 fs from a Kerr-lens mode-locked Ti:sapphire laser containing no intracavity prisms is demonstrated. In the femtosecond oscillator design reported, novel dielectric mirrors provide broadband dispersion control for solitonlike pulse formation.

The past few years have brought significant advances in ultrashort-pulse laser physics. The recent appearance of novel ultrabroadband solid-state laser materials motivated the development of new ultrafast optical modulation techniques that are capable of shaping optical pulses down to a few femtoseconds in duration. The discovery of self-mode locking[1] and the exploitation of a solitonlike interplay between self-phase modulation and negative group-delay dispersion[2] (GDD) have been the major steps toward a powerful new femtosecond laser technology based on broadband solid-state gain materials.

Besides the gain medium and an optical intracavity aperture, standard femtosecond self-mode-locked oscillators contain a pair of Brewster-angled prisms for producing a net negative GDD in the resonator. Prism pairs[3] have been widely used for intracavity dispersion control in dye systems and adopted for the new generation of solid-state short-pulse lasers. While it has been imperative that a prism pair be used for femtosecond mode locking of solid-state lasers, the prism pair also appeared to set a limit to pulse shortening in sub-100-fs systems. Only the use of selected prism materials permitted the generation of sub-20-fs pulses in Ti:sapphire lasers.[4,5] Nevertheless, cubic dispersion still represents the major limitation, even in systems optimized for minimum prism-induced phase error. As a consequence, the spectra of the sub-20-fs pulses from prism-pair-controlled oscillators are inherently asymmetric and tend to exhibit a pronounced broad shoulder when the narrowest autocorrelation traces are measured. An additional problem in this time domain is the increased sensitivity of pulse width to cavity and prism alignment. Cavity mirror alignment changes the position of the resonator axis and thus the glass path through the prisms. Hence any small cavity realignment calls for a subsequent readjustment of the prism insertion(s) and orientations to restore the original pulse width.

In this Letter we report on a novel technology for cavity GDD control that is free from these drawbacks. We demonstrate what is to our knowledge the first GDD control over a bandwidth as broad as 80 THz in a femtosecond laser by using chirped dielectric mirrors as the source of broadband negative GDD. Our results suggest that engineering the phase-dispersion characteristics of cavity mirrors opens the way toward a new generation of mirror-dispersion-controlled (MDC) oscillators, which are more compact, reliable, and user friendly than any previous femtosecond laser and can produce pulses down to the 10-fs regime.

The idea of employing specifically designed dielectric mirrors for intracavity chirp compensation is not new. Gires–Tournois interferometers and double-stack mirrors were designed and tested in femtosecond laser cavities previously.[6,7] These devices provided a simple and powerful means of controlling the net intracavity dispersion; however, they proved unsuccessful in supporting pulses shorter than 50 fs. This is due to the rapid variation of GDD with wavelength (high-order dispersion), which relates to the physical origin of dispersions in these dielectric mirrors: the incident field energy is temporarily captured in Fabry–Perot-like resonant structures, and the frequency dependence of the group delay (and of the GDD) results from that of the energy storage time.[8]

Recently we reported a new physical concept that can be exploited for broadband and essentially high-order dispersion-free GDD control with multilayer dielectric mirrors.[9] Briefly, by modulating the multilayer period during the deposition a chirped quasi-quarter-wave dielectric coating is fabricated. The variation of the layer optical thickness gives rise to a field penetration depth that is dependent on the (carrier) frequency and thus on the group delay suffered by different frequency components on reflection on the mirror. By careful design a near-linear variation of the group delay with frequency can be realized over the entire high-reflectivity wavelength range. The bandwidth of chirped mirrors can potentially be even broader than that of standard single-stack quarter-wave mirrors.

Using this concept, we have produced a chirped

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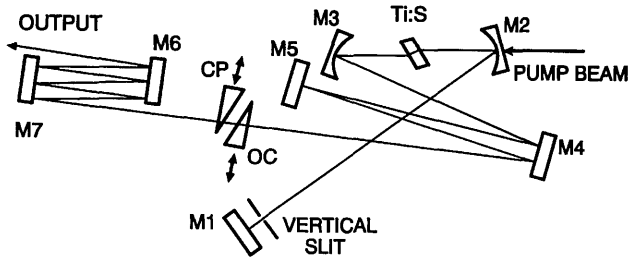

Fig. 1. Schematic of the MDC femtosecond Ti:sapphire (Ti:S) laser. M1, M4–M7, chirped dispersive mirrors described in the text; M2, M3, single-stack $\lambda/4$ dichroic mirrors highly transmitting at the pump wavelengths with radii of curvature of 5 cm; OC, 5% output coupler; CP, wedged glass plate compensating for the angular wavelength spread introduced by the output coupler. With a fixed number of bounces on M6 and M7 the extracavity GDD is fine tuned by translation of CP or OC.

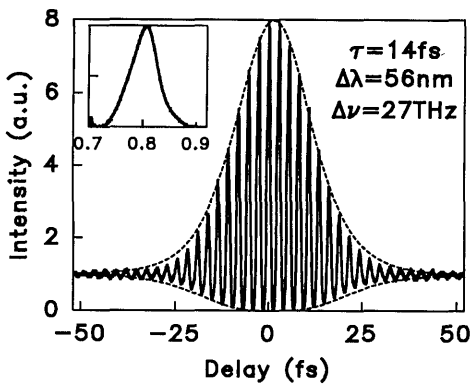

Fig. 2. Fringe-resolved autocorrelation and spectrum (wavelength unit, micrometers) of the femtosecond pulse train generated by the system outlined in Fig. 1. With the exception of the dielectric beam splitter of the autocorrelator, the extracavity beam-steering and focusing optics consist exclusively of Au-coated unprotected mirrors.

dielectric mirror that consists of 42 alternating layers of SiO_2 and TiO_2 with optical thicknesses close to a quarter of 0.8 μm, our desired center wavelength. The mirrors have a high-reflectivity ($R > 99\%$) range from 710 to 900 nm and a nominal GDD of -45 fs^2 at 800 nm with a variation of less than ± 5 fs^2 over the wavelength range of 720–890 nm.[10] (For further details see Ref. 9.)

To test these novel dispersive devices, we constructed an Ar-laser-pumped Kerr-lens mode-locked Ti:sapphire laser. In an effort to minimize the positive material GDD to be compensated for, we used a highly doped, 1.8-mm-thick Ti:sapphire plate (Crystal Systems) with a figure of merit of >150 as the gain medium. This has enabled us to achieve reliable mode-locked operation with the resonator beam bouncing just seven times off the dispersive mirrors on one round trip in the resonator (Fig. 1). The crystal inserted at Brewster's angle absorbs ≈70% of the incident pump power at 488 and 514 nm. For a pump power of 3.5 W, the oscillator in Fig. 1 delivers ≈300 mW of cw output power. We have accomplished Kerr-lens mode locking with a vertical slit, following the optimization recipe described in Ref. 5. With appropriate extracavity GDD control (by either a four-prism sequence or a pair of dispersive mirrors as shown in Fig. 1) this oscillator generates almost perfect sech^2-shaped pulses of 13–15 fs in duration with time–bandwidth products of ≈0.35 at a repetition rate of ≈100 MHz. Figure 2 shows a typical interferometric autocorrelation trace and the corresponding spectrum of the laser output. The mode-locked average output power is between 150 and 200 mW for pump powers of 3–3.5 W. Femtosecond pulse generation can be started by tapping one of the cavity mirrors with pump powers exceeding 1.5 W.

Comparison of Fig. 2 with previously reported results obtained with prism-pair-controlled systems[4,5] reveals that the pulse quality (in terms of spectral symmetry and fitting the theoretical sech^2 envelopes) of the MDC Ti:sapphire laser is far superior to that produced by its prism-pair-controlled forerunners. The excellent pulse quality of this MDC laser is a result of the weak dependence of the cavity GDD on wavelength over a broad spectral range, as revealed by Fig. 3 (solid curve). The absence of a monotonic increase or decrease of the net cavity GDD indicates that the cavity is essentially free from cubic dispersion over almost the entire mirror (or cavity) bandwidth. Interestingly, soliton formation appears to show very little sensitivity to the oscillatory behavior of the GDD versus wavelength.

The present oscillator design does not permit a precise adjustment of the intracavity dispersion; the GDD can be changed by discrete amounts only by a change in the number of reflections on the dispersive mirrors. With 11 bounces the laser generates pulses of ≈30 fs, implying an ≈4-fs/bounce increase in pulse duration. The fact that the 30-fs oscillator shows no degradation in output power indicates that the chirped mirrors have low scattering and absorption losses, offering the possibility of using even more bounces either to produce longer pulses or to compensate for more material dispersion if required.[11] We have also attempted to reduce the number of bounces and found that reproducible mode-locked operation cannot be achieved with fewer than seven reflections with our dispersive mirrors. To reduce

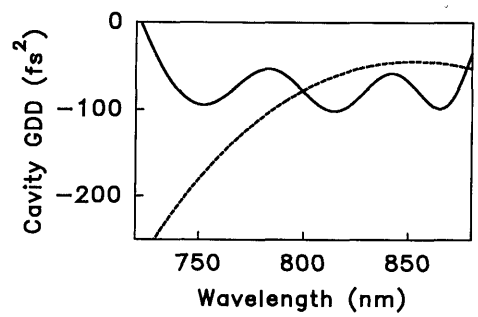

Fig. 3. Overall intracavity GDD (solid curve) versus wavelength for the system illustrated in Fig. 1. This can be compared with the dispersion curve of the same Ti:sapphire laser with a pair of fused-silica prisms (dashed curve). An assumed minimum prism insertion of 4 mm and a required nominal GDD of -80 fs^2 yielded a prism separation of 34.4 cm.

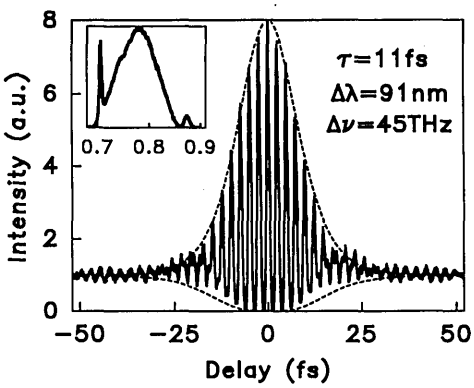

Fig. 4. Fringe-resolved autocorrelation trace and spectrum (wavelength unit, micrometers) of the mode-locked MDC Ti:sapphire laser with mirror M1 (Fig. 1) replaced by a similar dispersive mirror having a slightly lower negative GDD and larger negative cubic dispersion. The resonance spikes indicate roughly the boundaries of the wavelength range where the overall cavity dispersion is negative. The time–bandwidth of product of ≈0.49 implies that the pulses carry some chirp, caused presumably by the finite width of the negative dispersion range.

the negative cavity GDD by a smaller amount, we replaced mirror M1 with a mirror of similar design that exhibits a slightly lower negative GDD. With the net negative GDD reduced this way, our MDC Ti:sapphire laser produces reproducible optical pulses of ≈11 fs, with typical output characteristics shown in Fig. 4. Further pulse shortening in the present system is limited by the lack of fine tuning of the GDD and ultimately by the bandwidth of negative cavity GDD.

Other than the achievable pulse width, stability and reproducibility are the most important demands on a practical femtosecond source. The extremely simple and compact setup has resulted in what is to our knowledge unprecedented stability in the 10-fs regime. The fluctuation of the second harmonic of the mode-locked laser output has been measured to be ≈1% (rms) in the frequency band between 0.01 and 20 Hz, where the most intense environmental perturbations occur. The high stability of the mode-locked laser is also confirmed by the smooth spectra recorded with the combination of a scanning monochromator and a digitizing oscilloscope (scanning rate 9 nm/s, sampling rate 200 Hz). The results presented above have also an excellent day-to-day reproducibility. Once the laser is mode locked it automatically delivers pulses in the 10–15-fs range without any further optimization. This is because the cavity GDD is completely insensitive to resonator alignment, in strong contrast to prism-controlled systems. These features make the novel family of MDC femtosecond lasers ideally suitable for use as front-end oscillators in complex femtosecond amplifier systems.

Besides the benefits discussed above, the replacement of prisms by dispersive mirrors also removes a constraint set by the minimum prism separation on the resonator length and thus opens the way toward the development of high-repetition femtosecond Kerr-lens mode-locked systems. As with any kind of multilayer dielectric coating, the dispersion and reflectivity characteristics of a chirped multilayer mirror design for a particular center wavelength can be easily reproduced for different spectral regions by simple rescaling of the layer thicknesses. This feature will permit an easy reproduction of the MDC Ti:sapphire laser performance in other broadband solid-state-lasers. It may be anticipated that engineering the cavity mirror dispersion will permit the development of a reliable sub-10-fs oscillator technology for the visible and near-infrared spectral ranges.

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10. This variation does not include a slight linear decrease in negative GDD with wavelength (i.e., negative cubic dispersion), which helpfully compensates for a significant part of the positive cubic material dispersion in the laser cavity.
11. Note, however, that more material in the cavity (and consequently more bounces on the dispersive mirrors) will increase the fluctuation of the net GDD with respect to its mean (or nominal) value.