Ultrabroadband ring oscillator for sub-10-fs pulse generation

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A four-mirror ring cavity formed by chirped dielectric mirrors is proposed for self-mode-locked solid-state lasers. It offers, for the first time to our knowledge, the potential for approaching the gain-bandwidth limit in Ti:sapphire and related broadband lasers. Using this concept, we produced nearly bandwidth-limited 7.5-fs pulses from a feedback-initiated, self-mode-locked Ti:sapphire ring oscillator. Our experiments provide new insight into the physics and limitations of sub-10–fs oscillators. © 1996 Optical Society of America

The performance of prism-controlled lasers operating in the 10-fs regime[1,2] has been limited by the finite high-reflectivity bandwidth of quarter-wave dielectric mirrors and by the finite constant group-delay-dispersion (GDD) bandwidth $\Delta\nu_{\mathrm{GDD}}$ of the oscillator. Chirped multilayer dielectric mirrors[3] used for both feedback and intracavity dispersion control (mirror dispersion control, MDC) in femtosecond oscillators promises to push the current limits of ultrafast laser technology. However, linear cavities, in which the MDC concept was previously implemented[4] suffer from a few severe shortcomings, preventing full exploitation of the potential of the MDC technology for ultrashort pulse generation. Recently the MDC concept was implemented in a ring cavity.[5] We show that innovations in the cavity design and the chirped mirrors potentially will allow self-mode-locked MDC ring oscillators to approach the gain-bandwidth limit in Ti:sapphire and other broadband vibronic lasers.

A major limitation in linear-cavity short-pulse oscillators stems from the limited bandwidth of a low-transmittivity multilayer output coupler. The other principal drawback of a linear cavity lies in the fact that a thin wedged glass plate, which would be needed in a MDC oscillator for fine tuning the intracavity dispersion, severely impedes the start-up of passive mode locking because of étalon effects.

To overcome these shortcomings we have developed a MDC ring oscillator with a thin, highly doped Ti:sapphire crystal (path length 1.95 mm) as the gain medium. Recent progress in chirped-mirror technology permitted the fabrication of dichroic chirped mirrors that are transparent at pump wavelengths of 488 and 514 nm. As a result, an all-chirped-mirror cavity could be constructed for what we believe to be the first time. The 175-MHz ring cavity shown in Fig. 1 is formed by four chirped mirrors, which are selected for maximum $\Delta\nu_{\mathrm{GDD}}$.

Output coupling can be realized by use of a low-reflectivity coating deposited onto a slightly wedged (≈1.6°), thin (≈0.1–0.8-mm) quartz substrate, which is placed at Brewster's angle in the cavity. In contrast to a linear cavity, a low-reflectivity output coupler does not compromise the efficiency by producing two outputs because Kerr-lens mode locking (KLM) is unidirectional.[5,6] Angular dispersion introduced by the output coupler substrate is compensated by an identical uncoated compensation plate placed in close proximity to the output coupler. Translation of this plate provides a simple means of controlling the cavity GDD. Owing to feedback initiation of pulse formation,[6] the presence of thin plates does not inhibit the buildup of passive mode locking as is often the case in linear resonators. As a consequence, the ring cavity design shown in Fig. 1 removes the shortcomings of previously realized linear systems.

Following the design guidelines of Lin *et al.*,[7] KLM is accomplished with an aperture ≈20 cm apart from M1 in the collimated section of the resonator with the curved mirrors adjusted to the far boundary of the stability range. To our knowledge, this is the first demonstration of hard-aperture KLM in a ring laser. Previously, the soft gain aperture was utilized for KLM in Ti:sapphire ring oscillators.[5,6,8] We were also able to achieve soft-aperture mode locking; however, in the sub-10-fs regime the use of the hard aperture provided much more stable and much more reliable operation. We initiated femtosecond pulse formation by feeding back the output resulting from the radiation that circulates clockwise in the free-running laser as demonstrated by Pelouch *et al.*[6]

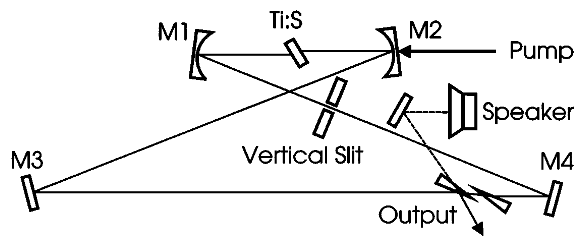

Fig. 1. Schematic of the MDC Ti:sapphire (Ti:S) ring laser. The pump beam is focused with a 40-mm lens onto the Ti:S crystal. M1, M3, M4, chirped mirrors; M2, chirped dichroic mirror. The radius of curvature of M1 and M2 is 50 mm.

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We used an uncoated wedge ($\theta = 1.6°$) as an output coupler at an incidence angle slightly off Brewster's angle to provide a reflectivity of ≈0.8%. The reflectivity of the other side, which was 1.6° closer to Brewster's angle, was measured to be ≈0.2%. The total insertion loss of the compensation plate was ≈2%. At pump powers of 5–6 W the total cw output was typically 80–100 mW. When ~5% loss was introduced with the aperture, the output dropped to less than 20 mW, and the unidirectional mode-locked output power was 20–25 mW. More recently, a 5%-reflecting output coupler yielded an average output power of 150 mW without any appreciable change in the mode-locking performance.

The nominal values of the GDD of the different cavity components (at 800 nm) are given in Table 1. Interestingly, the dispersion of air provides a nonnegligible contribution to the net cavity dispersion. With the optical path lengths in the quartz plates minimized, we obtain a maximum net negative GDD of $D = -(18 \pm 10)$ fs^2 at 800 nm. We can reduce this value further by translating the compensation plate. The fringe-resolved autocorrelation (FRAC) and spectrum of the mode-locked laser for optimum glass insertion are shown in Figs. 2(a) and 2(b), respectively. The extracavity dispersion is controlled by a pair of chirped mirrors and a pair of thin wedged quartz plates. The beam is steered with unprotected gold mirrors, and the FRAC is measured with a 15-μm-thick BBO crystal. Assuming a sech^2 pulse shape, we have evaluated a pulse duration of 7.5 fs from the measured FRAC trace. Fourier transformation of the spectra measured at different positions in the output beam (not corrected for the detector and the monochromator responses) yields pulse widths of between 7.5 and 8 fs, depending on the position of the measurement across the beam.

As revealed by Fig. 2(b), the pulses carry some spatial chirp in the horizontal plane, which is presumably introduced by the Brewster-angled gain medium. This chirp causes a pulse-front tilt,[10] which gives rise to a broadening of the pulse at the beam focus. Although the spatial chirp could be completely removed by an extracavity quartz prism pair (10° prisms 1.7 m apart), the pulses broadened to >8 fs rather than becoming shorter, presumably owing to cubic dispersion introduced by the prisms. From the observed spatial chirp a pulse broadening of ≈0.7 fs was inferred at the beam focus. Hence we conclude that simultaneous control of spatial chirp and high-order dispersion external to the cavity will permit generation of 7-fs pulses from this oscillator.

Notice that the mode-locked spectrum extends from ≈680 to ≈920 nm, over a bandwidth that is currently achievable only in an all-chirped-mirror cavity (quarter-wave mirrors centered at 800 nm have a high-reflectivity bandwidth of 180–200 nm). The overall high-reflectivity bandwidth of the chirped mirrors extends over more than 350 nm but is interrupted by a few resonances in the currently used mirrors. The one closest to the center laser wavelength is responsible for the narrow feature in the laser spectrum at ≈680 nm. These resonances could be eliminated in future mirror designs. A more severe limitation results from $\Delta\nu_{\mathrm{GDD}}$, which is currently limited to the range of ≈710 to ≈890 nm. It is remarkable how smooth an well-shaped a spectrum can be produced at a nominal negative GDD as low as $D = -(18 \pm 10)$ fs^2. This demonstrates, on the one hand, the high quality of broadband dispersion control that was achieved. On the other hand, this result also shows that comparatively large fluctuations[4] ($\delta D_{\max} \approx \pm 20$ fs^2) of the net cavity GDD do not affect short-pulse formation if the period length of the fluctuations is small compared with the mode-locked bandwidth and the mean value of D is approximately constant.

To verify the extremely small calculated value of the net negative cavity GDD and gain further insight into the physics of a sub-10-fs oscillator, we measured the pulse parameters as a function of intracavity pulse energy and dispersion to compare the measured results with the theoretical prediction[11]:

$$\tau = [(3.53|D|)/\phi W] + 0.1\phi W\,, \tag{1}$$

where W is the intracavity pulse energy and ϕ is the Kerr-induced phase shift per unit power in the

Table 1. GDD of Components of the Ti:Sapphire Ring Oscillator Shown in Fig. 1

Cavity Component	GDD at 800 nm (fs^2)	Source
Chirped mirrors[a]	−170	Measured
Ti:sapphire crystal	+105	Measured
Quartz plates	+15	Calculated
Air	+32	Calculated
Total	−(18 ± 10)	

[a]Characterized by use of the technique described in Ref. 9.

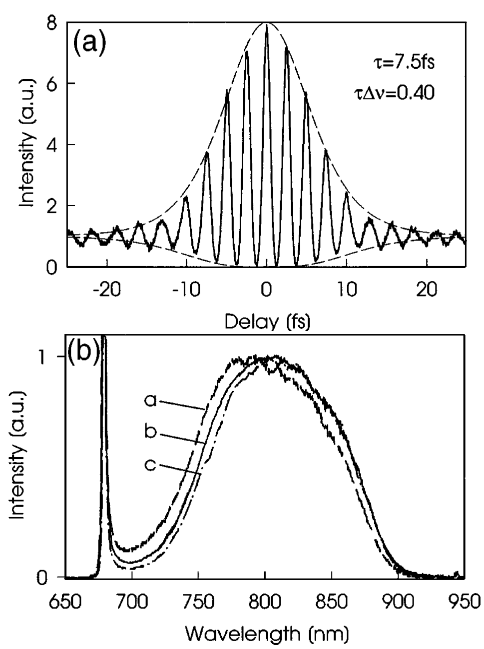

Fig. 2. (a) Single-scan FRAC trace of the output of the MDC Ti:sapphire laser. (b) Spectrum of the mode-locked laser measured through a pinhole positioned at (curve b) the center of the beam and (curves a and c) the half-intensity-maximum points in the horizontal plane. In the vertical plane no spatial chirp was observed.

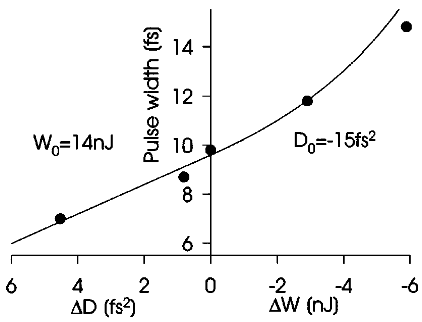

Fig. 3. Pulse duration (corrected for spatial chirp) as a function of the intracavity dispersion D at a constant intracavity pulse energy W (left-hand side) and as a function of W at constant D (right-hand side). $\Delta D = D - D_0$ is the relative change of D with respect to $D_0 = -15\ \mathrm{fs}^2$, and $\Delta W = W - W_0$ stands for the relative change of W with respect to $W_0 = 14$ nJ. The solid curve is a theoretical fit of Eq. (1), from which $D_0 = -15\ \mathrm{fs}^2$ and $\phi = 0.42 \times 10^{-6}\ \mathrm{W}^{-1}$ are obtained.

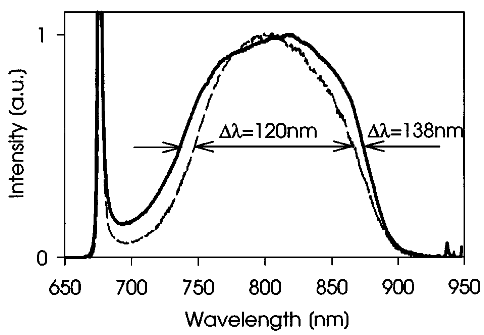

Fig. 4. Mode-locked spectra (measured at the beam center) obtained with an elliptical aperture (solid curve) and with a vertical slit (dashed curve).

gain medium. Figure 3 shows the measured pulse widths (corrected for spatial chirp) versus D and W. With a maximum negative dispersion of $D = -15\ \mathrm{fs}^2$ and $\phi = 0.42 \times 10^{-6}\ \mathrm{W}^{-1}$ the theoretical curve obtained from Eq. (1) fits the experimental data well. The evaluated cavity GDD confirms the value obtained when we total the measured or the calculated GDD of the individual cavity components (Table 1). The value of the other fit parameter is also consistent with that obtained previously for a linear-cavity KLM laser.[1] Also, the good agreement between Eq. (1) and the measured data depicted in Fig. 3 strongly suggests that solitonlike shaping is the dominant pulse-shaping mechanism down to pulse durations as short as 7 fs. This performance was obtained without the presence of negative fourth-order dispersion in the cavity, contradicting recent theoretical predictions.[12]

Finally, we address the question of what limits the performance of this system. Aiming to produce shorter pulses, we tried to reduce the negative dispersion below the value corresponding to the shortest pulse duration in Fig. 3. But the laser either became unstable or dropped out of the mode-locked state. To keep mode locking stable at either lower values of $|D|$ or higher values of W we attempted to enhance the self-amplitude-modulation (or KLM) action by replacing the vertical slit with an elliptical aperture, which followed more closely the KLM-induced change in the beam profile. We were able to generate mode-locked spectra with significantly broader FWHM's (Fig. 4); nevertheless we did not achieve any noticeable reduction in pulse width. This result has two important implications: (1) the importance of effective self-amplitude modulation for producing the shortest pulses is evident even though solitonlike shaping determines the steady-state pulse width and (2) the finite $\Delta\nu_{GDD}$ prevents the overall mode-locked spectrum (i.e., the tails) from being extended any further; hence it constitutes the principal limitation to further pulse shortening in this system.

We have demonstrated a mirror-dispersion-controlled Ti:sapphire ring oscillator that is formed exclusively by chirped mirrors. As a result of an extremely low negative dispersion, which, together with the well–behaved spectrum, evidences phase-error-free dispersion control of unprecedented quality, this system can generate nearly bandwidth-limited 7-fs optical pulses if spatial chirp and cubic dispersion can be simultaneously controlled outside the cavity. More important, the minimum pulse duration was shown to be limited merely by the constant-GDD bandwidth of the oscillator, which is determined by those dispersive characteristics of the mirrors that can be engineered. Hence, this system offers, for the first time to our knowledge, the potential for approaching the gain-bandwidth limit in Ti:sapphire.

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