Self-starting 6.5-fs pulses from a Ti:sapphire laser

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We demonstrate self-starting 6.5-fs pulses from a Kerr-lens mode-locked Ti:sapphire laser with 200-mW average output power at a pulse repetition rate of ≈86 MHz. This is to our knowledge the shortest pulse ever generated directly from a laser. For dispersion compensation we used a prism pair in combination with double-chirped mirrors, which balances the higher-order dispersion of the prism pair and therefore flattens the average total group-delay dispersion in the laser cavity. For self-starting mode locking we used a broadband semiconductor saturable-absorber mirror. © 1997 Optical Society of America

Over the past few years considerable progress has been made in ultrashort pulse generation by Ti:sapphire lasers. Pulses as short as 7.5 fs have been demonstrated directly from the laser oscillator.[1,2] This rapid progress in pulse-width reduction is mainly based on improvements in dispersion compensation[2,3] and on Kerr-lens mode locking (KLM).[4–7] However, pure KLM pulses in the 10-fs regime are typically not self-starting and require a critical cavity alignment. Recently, we demonstrated self-starting pulses as short as 10 fs, using a broadband semiconductor saturable-absorber mirror (SESAM) to start KLM and to relax the critical cavity-alignment requirements.[8] The pulse width was limited by the remaining higher-order dispersion in the laser cavity, which was caused mainly by the prism pair.[1] However, the prism pair has the advantage that the desired negative second-order dispersion can be adjusted continuously.[9]

In this Letter we demonstrate self-starting 6.5-fs pulses (Fig. 1) with 200-mW average output power, using prism pairs in combination with a double-chirped mirror[10] for higher-order dispersion compensation. The result is an increased wavelength range in which the average negative group-delay dispersion (GDD) is made constant. To our knowledge these are currently the shortest pulses generated directly from a laser. The same broadband SESAM as that described in Ref. 8 is used to self-start the mode-locking process in the Ti:sapphire laser.

The laser (Fig. 2) is built in a standard delta configuration and pumped by 5 W of an argon-ion laser. The Ti:sapphire laser resonator consists of three 10-cm radius-of-curvature highly reflective focusing mirrors (Spectra Physics) and a 2.3-mm-thick Ti:sapphire laser crystal (0.25% doping). The dispersion compensation is achieved by use of a pair of fused-silica prisms in one laser arm and a double-chirped mirror[10] that folds the other laser arm, which results in two bounces per round trip. The prisms have a separation of 40 cm and allow for a continuous adjustment of the necessary negative second-order dispersion over a range of at least 450 fs^2.[9] Self-starting is obtained with a broadband SESAM, which corresponds to a low-finesse antiresonant Fabry–Perot saturable absorber with a silver mirror as the lower Fabry–Perot reflector and a 15-nm-thick low-temperature molecular-beam epitaxy grown GaAs absorber (Fig. 2a in Ref. 8). More details on the SESAM devices are presented elsewhere.[11,12] We measured a mode-locking buildup time of ≈3 ms. The 3-mm-thick 3% output coupler and the additional glass used for the pulse diagnostics are compensated externally by chirped mirrors provided by Szipöcs.[3]

The interferometric autocorrelation (IAC) of the pulse (Fig. 1) was measured with a KDP crystal wedged from 50 to ≈7 μm. The beam splitter in the autocorrelator consists of gold-coated, 0.2-mm-thick fused-silica plates, so dispersive pulse broadening is minimized. The autocorrelator was calibrated with a He–Ne laser. For the measurement of the spectrum, we used a standard optical spectrometer consisting of an entrance slit, a blazed grating, and a silicon CCD–photodiode array (Jobin Yvon).

The dominant pulse-shaping mechanisms within one round trip in the resonator are the total negative GDD and the self-phase modulation (SPM) occurring in the laser crystal. Therefore the necessary negative GDD can be estimated from the formulas that are valid for an ideal average soliton according to[13]

$$D = \frac{\mathrm{d}T_g}{\mathrm{d}\omega} = -2\phi_0\left(\frac{\tau_{\mathrm{FWHM}}}{1.76}\right)^2, \quad \phi_0 = \frac{1}{2}\delta|A_0|^2, \qquad (1)$$

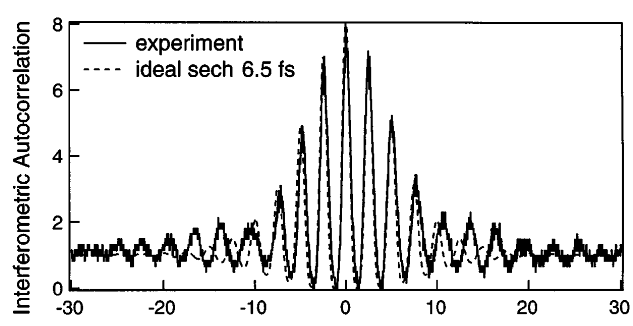

Fig. 1. Interferometric autocorrelation of a self-starting KLM pulse compared with an ideal 6.5-fs pulse at 750 nm.

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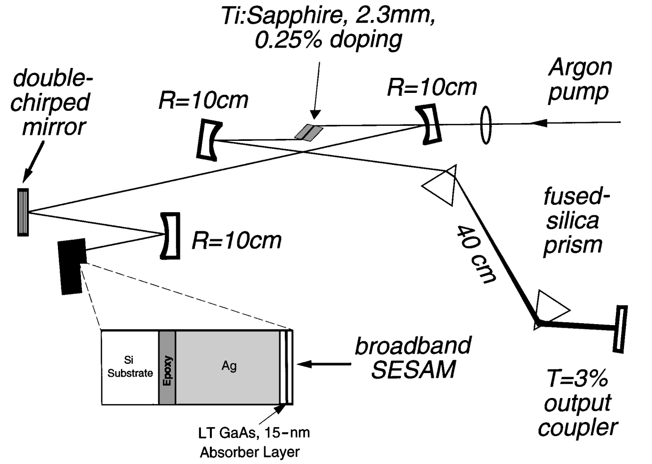

Fig. 2. Ti:sapphire laser design with one flat double-chirped mirror and a broadband SESAM for self-starting KLM.

where T_g is the total intracavity group delay within one round trip, ϕ_0 is the nonlinear phase shift of the soliton per round trip, τ_{FWHM} is the pulse duration, δ is the SPM coefficient and $|A_0|^2$ is the soliton peak power. With a peak power of 11 MW and a SPM coefficient of $\sim$0.07/MW, we estimate the necessary negative GDD to be $D = -10\ \mathrm{fs}^2$. However, the SPM coefficient is not known precisely, because it is proportional to the effective area of the laser mode in the laser crystal and, therefore, can only be estimated from ABCD-matrix calculations of the laser cavity. The action of the SPM on the pulse also depends on the actual pulse width during passage of the laser crystal. For optimal pulse shaping the net GDD should be constant over as large a wavelength range as possible. The estimated resolution for the measured GDD (Ref. 14) is $\pm 5\ \mathrm{fs}^2$. Figure 3(a) shows the measured GDD that is due to one reflection on the double-chirped mirror and on a standard dielectric mirror (Spectra Physics). The bold curve corresponds to the average GDD of the double-chirped mirror. Furthermore, Fig. 3(a) shows the calculated cavity round-trip GDD, taking into account the laser crystal and the prism pair with 40-cm prism–prism separation and 6.6-mm total prism insertion. The calculated GDD of the laser crystal per round trip is $+304\ \mathrm{fs}^2$. We obtain the total intracavity GDD by multiplying the GDD curves of the mirrors by the number of bounces within one round trip and adding the resulting GDD of all intracavity elements [Fig. 3(b)]. At 800 nm, the double-chirped mirror provides an average value of roughly $-60\ \mathrm{fs}^2$ per bounce, whereas the dielectric mirrors show vanishing GDD. We can continuously adjust the prism pair to obtain the remaining $-194\ \mathrm{fs}^2 = (-2 \times 60 + 304 + 10)\ \mathrm{fs}^2$ plus the possible minor dispersion that is due to the air in the cavity.[2] The prisms can be adjusted for introduction of the optimum GDD for the shortest pulse without a precise knowledge of the SPM coefficient δ.

The higher-order dispersion of the prism pair is the most important limitation to ultrashort pulse generation.[1] The wavelength dependence of the GDD (Fig. 3) that is due to the prism pair dominates in comparison with all the other intracavity elements. At 845 nm, the GDD of the prism pair is maximum.[1] The standard dielectric mirrors (Spectra Physics) are highly reflective from $\sim$700 to 900 nm. Their GDD is very smooth; however, for sub-10-fs pulse generation, it can only be considered constant from 725 to 825 nm, half of the high-reflection bandwidth. The GDD strongly varies as it approaches the edges of the reflection zone. Therefore a broad spectral bandwidth of standard high reflectors does not imply that the GDD is constant over the same range. The contribution from the output coupler is less severe than the contribution from the standard high reflectors, and therefore it is not shown. The double-chirped mirror introduces large oscillations in the GDD. However, the mirror improves the average GDD in the laser cavity. Note that rapid oscillations in the GDD are not serious, because the physically important quantity, which shapes the pulse and regroups the spectral components in time, is the group delay, which is the integrated GDD. Of course, the oscillations have to stay below a certain limit. The average GDD of the double-chirped mirror was designed to show the inverse behavior of the GDD of the prism pair if three intracavity mirrors were used. Figure 3(b) shows the computed total GDD of the laser cavity without and with the double-chirped mirror, which we obtained using the fitted average of the measured GDD. This figure clearly shows that the double-chirped mirror flattens the average GDD over a larger spectral range. Thus the pulse experiences less average higher-order dispersion. However, the oscillations in the GDD, which currently are due to the limited number of layers in the double-chirped mirror design,[10] cause a modulation in the pulse spectrum. This limited us to only two bounces on the double-chirped mirror. We hope to improve on this in the near future.

Figure 4 shows the measured pulse spectrum with and without calibration and the calibration factor corresponding to the sensitivity of the spectrometer. The

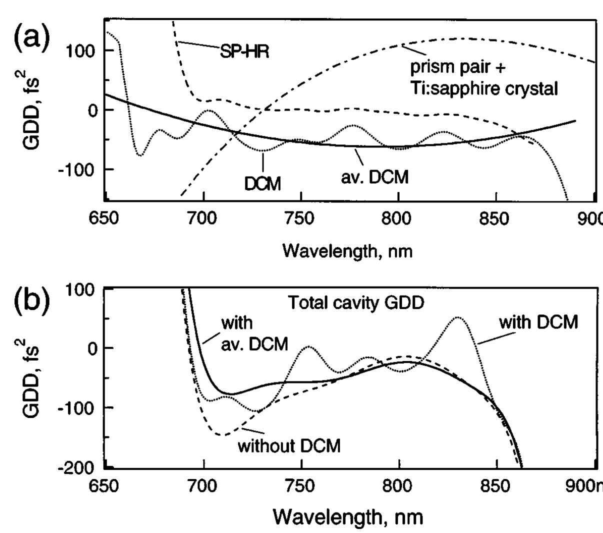

Fig. 3. (a) Group-delay dispersion (GDD) of all intracavity elements: DCM, double-chirped mirror; av., average; SP-HR, Spectra Physics high reflector. (b) Total intracavity GDD. The estimated resolution is $\pm 5\ \mathrm{fs}^2$.

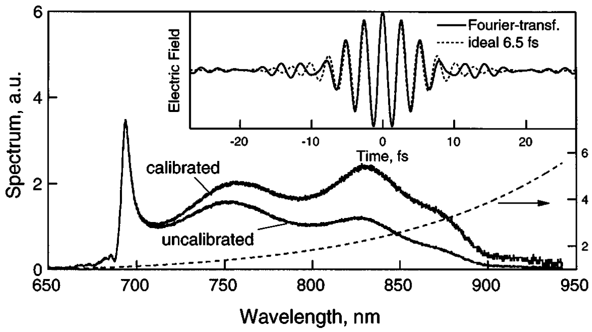

Fig. 4. Measured and calibrated pulse spectrum together with the calibration factor. The inset shows the electric field obtained by direct Fourier transform of the spectrum, assuming constant phase and the electric field of an ideal 6.5-fs sech pulse.

pulse spectrum changes slightly depending on the position of the laser beam on the spectrometer slit. This indicates the presence of a frequency-dependent mode size, which is typical in sub-10-fs KLM lasers[15] and needs further investigation. Therefore the acquisition of a correct broadband pulse spectrum still involves some uncertainties. The pulse spectrum itself shows significant deviations from an ideal sech^2 shape. We think they are caused mainly by the oscillations in the GDD of the double-chirped mirror. However, the double-chirped mirror is highly reflective from 650 to 900 nm with the potential for dispersion compensation over the same spectral range. Because of the bandwidth limitations that are due to the remaining standard dielectric mirrors, the pulse spectrum extends only from 690 to ~900 nm. The peak in the pulse spectrum at 690 nm, which is at the edge of the high-reflectivity range of the dielectric mirrors, is caused by phase matching between the soliton and the continuum, as first discussed in Ref. 16 and also observed for the previously reported 7.5-fs pulses.[2] We expect to make further improvements in the pulse width and the spectral shape by replacing all mirrors in the laser cavity with broadband double-chirped mirrors and by reducing the oscillations in the GDD with an increased number of dielectric layers in the mirrors in the near future.

It has been generally accepted that one should determine the pulse width from the measured IAC data by fitting the IAC of an ideal sech^2 pulse to the measured IAC whenever a solitary pulse formation can be considered.[1,2,17] Assuming that there was a sech^2 pulse shape, we evaluated a pulse duration of 6.5 fs from the measured IAC trace shown in Fig. 1. The main part of the autocorrelation trace fits remarkably well with the theoretical curve of an ideal 6.5-fs sech^2 pulse at a center wavelength of 750 nm. The period of the IAC fringes in the wings is slightly longer than in the center part of the IAC. This is an indication that the wings are caused mainly by additional spectral components at longer wavelengths, consistent with the measured calibrated spectrum. The inset in Fig. 4 shows the electric field resulting from the Fourier transform of the measured and calibrated spectrum, assuming a constant phase over the full spectrum and the electric field of the ideal 6.5-fs sech pulse. The pulse width resulting from the Fourier transformed spectrum is slightly longer. However, when we consider the uncertainties in the measured spectrum as discussed above, the agreement is reasonable, and we adopt the pulse width derived from the IAC, as has been done before.[1,2]

We have demonstrated self-starting 6.5-fs pulses from a KLM Ti:sapphire laser that uses prism pairs in combination with a double-chirped mirror. This mirror was designed to improve the net group-delay dispersion in the laser cavity over a broader spectral range. Self-starting is obtained by use of a broadband SESAM, which has proved to be a useful starting mechanism in the sub-10-fs regime. This approach has the potential for generating even shorter pulses in the near future.

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