Aberration-free stretcher design for ultrashort-pulse amplification

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A novel aberration-free pulse stretcher design is presented. This system permits the stretching of a 30-fs pulse to 300 ps and recompression to a duration of 33 fs, limited by the spectral clipping. © 1996 Optical Society of America

The amplification of sub-100-fs pulses to the terawatt peak power level has been performed by a number of research groups.[1,2] In such systems the onset of nonlinear effects and the risk of amplifier damage are minimized by exploitation of the technique of chirped-pulse amplification[3] (CPA). The goal in CPA systems is to amplify short pulses to high energy and to reproduce the input pulse temporally, with a minimum of residual pedestal. In order to do so, it is necessary to compensate all the residual chirp introduced during the stretching and amplification processes by using a matched pulse compressor. When the pulse duration approaches 30 fs, it becomes very difficult to eliminate the residual chirp over such a large spectral width. The uncompensated chirp results in a decrease in the achievable pulse contrast and imperfect recompression of the pulse. Since terawatt systems are used for intense light–matter interaction experiments in which pulse intensities onto a target can approach 10^{20} W/cm^2, it is important to have a large pulse dynamic range to prevent preionization of the target. In this Letter we present a novel pulse stretcher design based on the low-aberration all-reflective Öffner triplet,[4] which, when used in combination with an optimized CPA system, could provide ~30-fs pulses with high contrast. This Öffner design results in a larger dispersion in a compact package than does the standard design. Experimentally we demonstrate expansion of a 30-fs pulse to 300 ps and near-transform-limited recompression.

In CPA systems the seed pulse is temporally stretched when it passes through a positive delay line consisting of a pair of antiparallel diffraction gratings separated by a 1/1 telescope[5] (pulse stretcher). After the amplification the chirped pulse is recompressed when it passes through a negative delay line consisting of a pair of two parallel gratings[6] (pulse compressor). For a very low-level pedestal pulse to be obtained with an aberration-free stretcher configuration, three conditions must be satisfied. First, the spectral bandpass of the stretcher–compressor system has to be large enough to prevent spectral clipping. We deliberately limited the pulse duration to 30 fs in order to provide a high contrast ratio while keeping the optics size reasonable. Second, the material path length in the amplifier has to be minimized so that its high-order dispersion terms, uncompensated for by the compressor, do not affect the pulse shape. Third, the stretcher telescope has to be aberration free, since aberrations directly translate into spectral phase distortions, which produce poor recompression and a low dynamic range.

In practice, the finite size of the stretcher–compressor optics ultimately leads to some spectral clipping. The loss of part of the pulse spectrum, even at a few percent of the peak intensity level, affects the recompressed pulse duration and contrast.[7] In this Letter we define the contrast ratio as the ratio between the pulse intensity at $t = 0$ and the pulse intensity at $t = 3\tau$, where τ is the full width at half-maximum (FWHM) pulse duration. According to that definition, the contrast ratio is independent of the pulse duration. For a sech^2 pulse the contrast is then of 10^{-4}. Let us consider first the effect of spectral clipping. Figure 1 shows the calculated contrast and pulse duration as a function of the system bandpass for a 30-fs sech^2 input pulse (22 nm FWHM). Since the contrast ratio of a 30-fs pulse delivered by an optimized Kerr-lens mode-locked oscillator is usually limited to 10^{-4},[8] a good trade-off is provided by use of a 100-nm bandpass stretcher–compressor system.

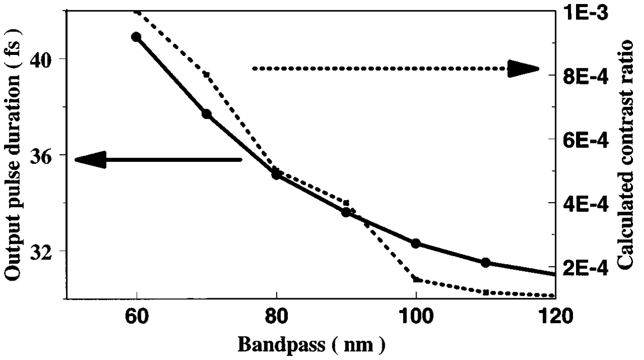

Fig. 1. Calculated contrast ratio defined as $I(t = 0)/I(t = 3\tau_{\mathrm{FWHM}})$ and output pulse duration (τ_{FWHM}) as a function of the bandpass for a 30-fs sech^2 pulse.

In the design of our stretcher we use a global approach instead of using a step-by-step approach and trying to compensate for higher-order dispersion terms independently. We first analyzed a compressor design that can be considered perfect from a geometrical-optics point of view. In order to be matched, the stretcher must be equivalent to the compressor with a negative effective length. This means that the image of the first grating through the optical components of the stretcher must be a perfect grating of the same characteristics. In conventional pulse stretchers, lens telescopes are regularly used; however, for the pulse durations below 100 fs, such refractive elements introduce strong chromatic aberrations. In a geometric aberration-free system it is therefore necessary to use reflective optics. The telescope in an ideal stretcher has to satisfy three conditions: it has to present a magnification equal to -1; the image of the first grating has to be perfectly stigmatic on the axis; and it has to present no on-axis coma, which means that the wavelength that is diffracted under an angle θ by the object grating has to intercept the second grating with exactly the same angle.

Our approach has been to look at an imaging system that presents these characteristics. Among the few solutions is an all-reflective triplet combination patented by Öffner in 1971.[4] The triplet combination is composed of two spherical concentric mirrors (see Fig. 2). The first mirror is concave, and the second one is convex. This combination presents interesting properties for use in a pulse stretcher. It is characterized by a complete symmetry, so only the symmetrical aberrations can appear, i.e., spherical aberration and astigmatism. But the presence of two spherical mirrors whose radius of curvature ratio is two and of opposite sign cancels these aberrations. This combination has no on-axis coma and exhibits no chromatic aberration, because all the optical elements are mirrors. In this optical combination, perfect stigmatism is ensured only when the object is at the common center of curvature.[9] When the object moves away from the center of curvature, the image quality is affected and spectral phase distortions appear, leading to a degradation in the temporal pulse profile.

Initially, we consider the optimum configuration in which the object grating is in the plane of the center of curvature and the second mirror is 500 mm away from the first one. The stretcher is used in a double-pass configuration with a roof prism, producing a stretching factor of 10,000 for a 30-fs input pulse. This stretcher is followed by a compressor consisting of a grating pair placed 1 m apart used in a double-pass configuration. We use our numerical code to model the propagation of a 30-fs sech^2 pulse through the stretcher. The recompressed pulse duration is 33 fs at half-maximum with a contrast ratio of 1.6×10^{-4}. That temporal pulse profile is identical to the calculated profile when only spectral clipping is considered. Indeed the phase distortions are almost zero (less than 10^{-8} rad peak to peak) within the numerical precision of the calculations. In such a configuration the adjustment and the tunability of the stretcher are not trivial because of the presence of two gratings. An error in the parallelism of the gratings can lead to a spatially chirped pulse profile.

An alternative combination is to use a single grating placed out of the plane of the center of curvature. In our design the grating is placed 250 mm away from the center of curvature and provides an expansion coefficient of 10,000 in a double-pass configuration. The drawback of such an arrangement is the presence of spherical aberration, since the grating is out of the plane of the center of curvature. We confirmed that this aberration is weak enough not to affect the pulse shape. For a simulated 30-fs sech^2 input pulse passing through the stretcher and the compressor, the recompressed duration is again 33 fs with a contrast ratio equal to 1.6×10^{-4} (see Fig. 3). The temporal pulse profile is in fact limited only by the spectral clipping (compare with Fig. 1). This means that the additional aberrations of that configuration are still negligible. If we compare the residual phase of the two configurations, we find that the spherical aberration induces an increase of 2 orders of magnitude in the fourth order of dispersion [$\phi^{(4)} = -5 \times 10^4$ fs^4], which is not large enough to affect the pulse shape.

To confirm these findings we built a single grating stretcher similar to that described above (Fig. 2) and sent a 30-fs pulse through the system and then recompressed it, using a standard compressor. The grating has 1200 grooves/mm with a surface flatness of $\lambda/10$. The incidence angle is 38°, and the diffraction angle is 20.14° at $\lambda = 800$ nm. The Öffner triplet consists of a 1024-mm radius of curvature concave mirror

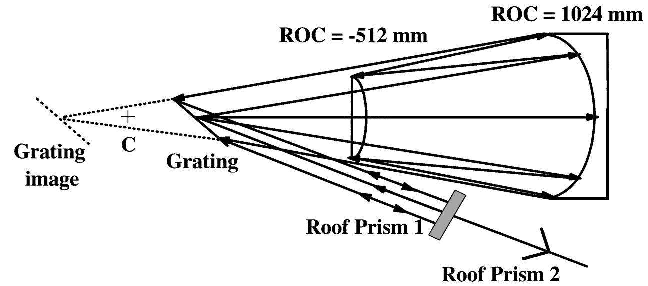

Fig. 2. Experimental setup of the aberration-free stretcher. C is the center of curvature of both mirrors. Roof prism 2 is used to double pass the stretcher. ROC, radius of curvature.

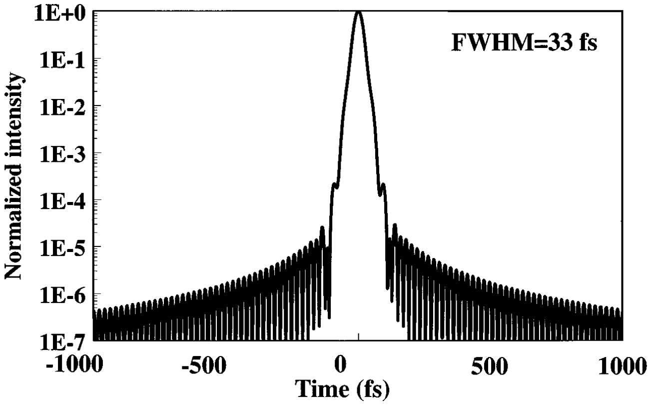

Fig. 3. Calculated temporal pulse profile after stretching through a single grating configuration and recompression in a pair of similar gratings.

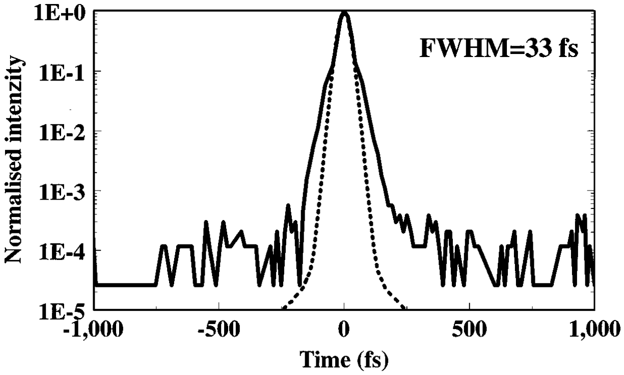

Fig. 4. Experimental autocorrelation (solid curve), on a logarithmic scale, of a stretched and recompressed pulse (FWHM 33 fs). The dotted curve is the calculated autocorrelation after propagation through the stretcher and the compressor (FWHM 33 fs). The initial pulse duration is 30 fs. The dynamic range is limited to 10^{-4} by the acquisition card used for the autocorrelation measurement.

(200-mm diameter) and a −512-mm radius of curvature convex mirror (120 mm long, 20 mm high). With these mirror sizes the stretcher bandpass is roughly 100 nm. The concave mirror exhibits a surface flatness of $\lambda/40$, and the convex mirror one of $\lambda/7$.

For a 30-fs incident pulse we obtained a recompressed duration of 33 fs, assuming a sech^2 pulse profile. The experimental and calculated (from the ray-tracing program) autocorrelations are presented in Fig. 4. The experimental autocorrelation shape is slightly different from the calculated one, but the wings that appear at 10^{-1} fall rapidly, and the experimental autocorrelation trace tends to join the theoretical one. The Fourier transform of the experimental spectrum coming out of the stretcher–compressor system, assuming no spectral phase on the electric field, does not exhibit wings at this level. The experimental wings can be associated with a pure spectral phase mismatch. The pedestals that appear at 2×10^{-5} on the calculated autocorrelation are due to the spectral clipping. We found little influence of the relative position of the two mirrors on the pulse shape.

During passage through the amplifier, the pulse experiences the effects of phase distortion caused by the different materials. One can compensate for the second and third orders of the phase distortion induced by the materials by changing the distance between the two gratings and by changing the incidence angle on the gratings of the compressor. However, it is more difficult to compensate for higher orders of dispersion, although the addition of lengths of specific materials has been demonstrated to provide dispersion compensation up to fourth order.[10] In that case, the system is optimized for a specific configuration. An alternative approach is to design a CPA system with minimized material path length and therefore to reduce the high-order phase distortion; such a system will be easy to use for different configurations of amplification, i.e., different pulse duration and different central wavelength. We use our three-dimensional ray-tracing program, which includes material dispersion effects, to calculate the pulse's temporal profile after it travels through the stretcher, amplification materials, and compressor group. The optimum grating separation and incidence angle for the compressor associated with a given stretcher configuration are automatically calculated by the code, in order to yield the best recompressed temporal pulse profile.

The material lengths that we use currently in our three-stage amplifier chain are 22 cm of Ti:sapphire and 8.4 cm of calcite, 3 cm of KDP, and 0.7 cm of fused silica. The calculations are realized if we consider a single grating stretcher configuration. When we take into account these materials between the stretcher and the compressor, we find an optimum setting of the compressor corresponding to an angle mismatch of 0.61° and a translation of +12.16 mm. This configuration gives a compromise among the different high-order dispersion terms, with a positive second order partially canceling a negative fourth order. The residual high-order terms are small and thus do not significantly affect the pulse profile. The output pulse duration is still 33 fs, with a very small asymmetry compared with the ideal spectral clipping limitation. The calculated contrast is 1.6×10^{-4}, showing that for small amounts of material good compensation and hence a good-quality pulse can be easily obtained.

In summary, we have developed an aberration-free stretcher designed for the production of very short-duration multiterawatt pulses. It provides a large expansion ratio with minimized phase distortion. When this design is used with the appropriate CPA laser chain (with minimized material path length) the output pulse is limited only by the spectral clipping. This system is part of a large-scale 10-Hz Ti:sapphire amplifier that has already produced greater than 10-TW, 45-fs pulses.

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References

1. C. P. J. Barty, C. L. Gordon III, and B. E. Lemoff, Opt. Lett. **19,** 1942 (1994).
2. J. Zhou, C. P. Huang, M. M. Murnane, and H. C. Kapteyn, Opt. Lett. **20,** 64 (1995).
3. D. Strickland and G. Mourou, Opt. Commun. **56,** 219 (1985).
4. A. Öffner, U.S. patent 3,748,015 (1971).
5. E. E. Martinez, IEEE J. Quantum Electron. **QE-23,** 59 (1987).
6. E. B. Treacy, IEEE J. Quantum Electron. **QE-5,** 454 (1969).
7. C. P. J. Barty, B. E. Lemoff, and C. L. Gordon III, Proc. SPIE **1861,** 6 (1993).
8. P. F. Curley, G. Darpentigny, G. Chériaux, J. P. Chambaret, and A. Antonetti, Opt. Commun. **120,** 71 (1995).
9. A. Suzuki, Appl. Opt. **22,** 3943, 3950 (1983).
10. B. E. Lemoff and C. P. J. Barty, Opt. Lett. **18,** 1651 (1993).