Adaptive femtosecond pulse compression

D. Yelin, D. Meshulach, and Y. Silberberg

Department of Physics of Complex Systems, The Weizmann Institute of Science, Rehovot 76100, Israel

Received July 14, 1997

A practical adaptive method for femtosecond optical pulse compression is demonstrated experimentally for the first time to our knowledge. The method is robust and capable of handling the general case of pulse compression, in which the input pulses are completely uncharacterized or partially characterized. © 1997 Optical Society of America

Considerable effort has been directed toward the generation of ultrashort optical pulses since the invention of mode-locked lasers. Novel techniques for broadband dispersion control now permit self-mode-locked Ti:sapphire lasers to directly produce 6.5-fs pulses.[1] Compression of pulses to the sub-5-fs level was recently demonstrated by combination of such techniques with novel spectral-broadening techniques in external pulse compressors.[2,3] Efficient pulse compression generally requires characterization of the pulses. Grating-pair[4] or prism-pair[5] compressors are commonly used mainly for compensation of second-order dispersion, and a combination of these compressors allows for simultaneous compensation for the second and the third orders.[6] Recently, chirped dielectric mirrors were tailored to produce negative group-velocity dispersion over a wide spectrum.[7] Chirped mirrors were used for compression of pulses to the sub-5-fs level.[2] In cases in which the pulses are uncharacterized, or when the spectral phase cannot be approximated by the leading terms of the corresponding Taylor expansion, these techniques cannot be used for efficient compression. Furthermore, practical considerations limit the use of such techniques in situations in which the pulse source undergoes slow variations in time. These limitations can be overcome by an adaptive approach.[8,9]

It is our purpose in this Letter to demonstrate experimentally, for the first time to our knowledge, adaptive femtosecond pulse compression. In our method the input pulses are modified according to a feedback measurement of the output pulses in an iterative fashion. The programmable pulse compressor allows for independent control of the individual spectral components of the incoming pulses, so that almost-arbitrary phase functions can be achieved for efficient compression. Therefore the adaptive approach removes one of the main difficulties associated with femtosecond pulse compression, namely, the need for characterization of the uncompressed pulses. Thus our adaptive technique, together with the ability to form almost-arbitrary spectral phase filtering, allows for efficient compression.

Important benefits would arise from the use of adaptive pulse compression. The adaptive scheme could be used not only to compress pulses but also to correct for slow variations of laser systems. In addition, once the optimal filter has been calculated as a result of the compression process, this filter essentially provides a measurement of the spectral phase. These data, together with the power spectrum, allow for full characterization of the pulses. This adaptive approach can be further extended toward quantum coherent control, in which the quantum system is adaptively steered toward its desired final state in an iterative fashion.[10] We demonstrate our method by compression of pulses obtained directly from our model-locked Ti:sapphire laser. The general case of pulse compression, in which the input pulses are completely uncharacterized is exploited, whereby a single-value feedback signal is used by a simulated annealing optimization procedure[8] for efficient compression.

The layout of the experimental setup for adaptive compression is shown in Fig. 1. This setup, based on that described in Ref. 8, is composed of three main blocks: a programmable pulse shaper, a feedback-measuring device, and a computer used for calculating and updating the spectral filter. Phase-only filtering was used for efficient spectral manipulation. At iteration i of the algorithm we measured time-integrated second-harmonic signal C_i of the output pulses, $C_i = \int I_i^{(2\omega)}(t)\mathrm{d}t$, where $I_i^{(2\omega)}(t)$ is the second-harmonic intensity of the output pulses. Since phase-only filtering involves no energy loss, and because of the nonlinear process involved, high-level feedback signals correspond to high peak pulses of short duration. Although this feedback signal cannot provide full

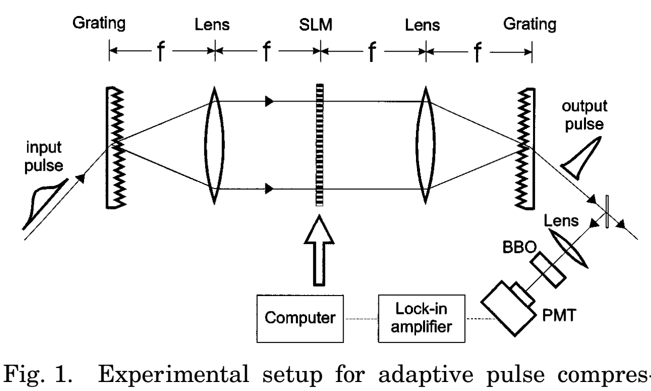

Fig. 1. Experimental setup for adaptive pulse compression. The setup consists of a nondispersive 4-f pulse shaper, a programmable SLM, a feedback-measurement arrangement, and a computer. For the feedback signal the output pulses were focused onto a BBO nonlinear crystal, and the second-harmonic signal was detected by a photomultiplier (PMT) with a lock-in amplifier.

0146-9592/97/231793-03$10.00/0

information about the shape of the pulses, we verified numerically for a variety of pulses that the feedback signal can be used for efficient compression.[8] For adaptive compression, we used a simulated annealing algorithm to maximize this feedback signal. Briefly, in each iteration a random change in the spectral filter is made, the feedback signal is measured, and a decision whether to accept this change is made.[8]

The femtosecond pulse source was a mode-locked Ti:sapphire laser, in which intracavity dispersion is compensated for by a prism-pair arrangement.[11] This laser normally produces pulses of sub-20-fs duration. The 4-f pulse shaper[12] is composed of a pair of thin holographic transmission gratings with 400 lines/mm and a pair of achromat lenses with a 100-mm focal length. The programmable one-dimensional liquid-crystal spatial light modulator (SLM) array (SLM-256; Cambridge Research and Instrumentation, Inc.) was placed at the Fourier plane of the shaper and used as an updatable filter for spectral manipulation of the incoming pulses. This SLM allows for independent control of the phase and amplitude of each of its 128 pixels,[13] although in this experiment it was used as a phase-only filter. The width of each pixel was 97 μm, the interpixel gap was 3 μm, and the spot size at the focal plane was ~80 μm. For the feedback signal we focused the output pulses with a lens with a focal length of 50 mm onto a 100-μm-thick frequency-doubling BBO crystal. The second-harmonic signal was detected by a photomultiplier with a lock-in amplifier. A computer read this signal, calculated the spectral filter, and updated the SLM.

To exploit the full potential of adaptive compression of pulses obtained directly from a laser, we adjusted our laser to produce a wide spectrum [inset of Fig. 2(a)]. In this case the pulses obtained were far from transform limited. An interferometric autocorrelation measurement of these pulses, shown in Fig. 2(a), implies strongly chirped pulses of 80 fs FWHM.

To obtain adaptive compression, we closed the feedback loop and monitored the increase of the second-harmonic signal as the process progressed. Interferometric autocorrelation measurements of the compressed pulses are shown in Fig. 2(b). In this case the optimization was performed with our simulated annealing algorithm with 1000 iterations. This result should be compared with the measurement of the uncompressed pulse shown in Fig. 2(a). Note the difference in the time scale between Figs. 2(a) and 2(b). The 80-fs input pulses were compressed to 14 fs. The feedback signal for this run in each iteration is shown in Fig. 3. The second-harmonic power increased by a factor of ~3 as a result of the optimization process. Since the pulses were compressed by a factor of ~5.7, we expect a similar increase in the second-harmonic signal. This difference can be attributed to energy loss in the SLM during the process and to residual negative dispersion of the shaper. Note that the rapid variations in the feedback signal are not noise but are due to the search procedure of the algorithm. In other runs pulses were compressed to 17 and 13 fs after 500 and 2000 iterations, respectively, suggesting a trade-off between the number of iterations and the duration of the resulting compressed pulses. It is somewhat surprising that such a relatively small number of iterations were needed for optimization of 128 independent phase terms; however, these results were consistent, and this form of convergence was typical of all runs.

The simulated annealing algorithm does not make use of any information about the uncompressed pulses. However, in many cases one can use some of this information to improve the optimization procedure. For example, the pulses exhibit dispersion that can be approximated by the leading terms of the corresponding Taylor expansion. To demonstrate how such information can improve the results, we developed an optimization algorithm for adaptive compression based on a search in the two-dimensional space of second- and third-order dispersion coefficients. We used this algorithm to compress the pulses directly from the laser [see Fig. 2(a)]. The interferometric autocorrelation measurement of the compressed pulses by use of this algorithm with 1200 iterations is shown in Fig. 4, from which we calculated that the pulses were compressed to 11 fs. A direct Fourier transformation of the input spectrum in the absence of any phase

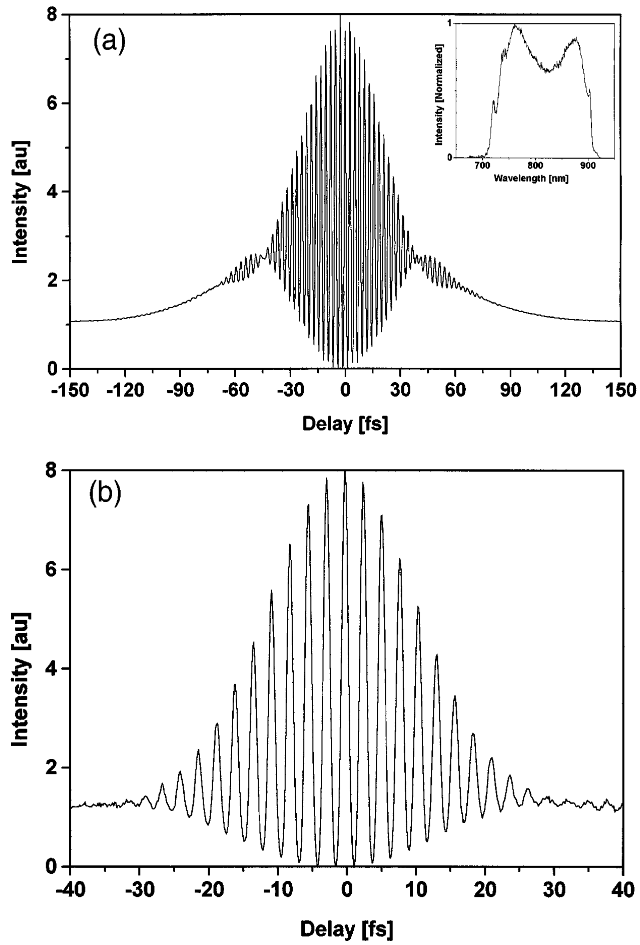

Fig. 2. Interferometric autocorrelation traces of the uncompressed and the compressed pulses. (a) Uncompressed 80-fs pulses obtained directly from the Ti:sapphire laser (the power spectrum is shown in the inset). (b) Compressed pulses after 1000 iterations. The pulses were compressed to 14 fs.

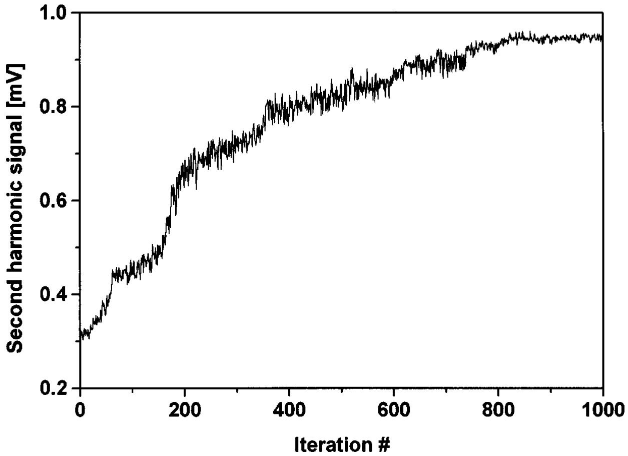

Fig. 3. Feedback signal as a function of the iteration number when a simulated annealing algorithm is used for compression.

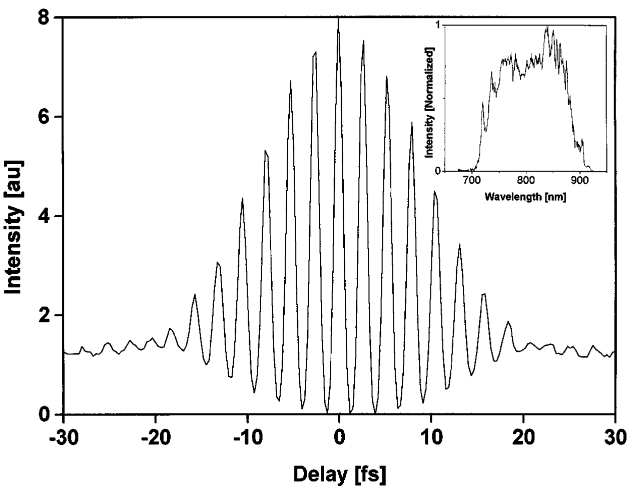

Fig. 4. Interferometric autocorrelation trace of the compressed pulses obtained with a two-dimensional search algorithm for second- and third-order dispersion coefficients, after 1200 iterations. The pulses were compressed to 11 fs. The power spectrum is shown in the inset.

modulation indicates that the spectrum can support a pulse as short as 9 fs. This result suggests that our laser pulses are chirped primarily by second- and third-order terms of the spectral phase.

Several issues regarding our scheme of adaptive compression should be discussed. Since adaptive compression is accomplished by maximization of the feedback signal, this method accounts not only for the spectral phase of the input pulses but also for any other phase distortions induced by the setup, such as residual dispersion of the shaper, the mirrors, and the SLM itself. Once an optimal phase function has been found, it provides an indirect measurement of all these phase distortions. Although compression was demonstrated for pulses emerging directly from the laser, which have smooth spectral phase variations, we believe that our scheme has the potential to compensate for almost-arbitrary spectral phase distortions, based on the performance of similar programmable pulse shapers.[8,9,13]

We note that the SLM imposes several limitations on the overall performance. Since spectral manipulation is accomplished by control over 128 discrete pixels, continuous filters cannot be realized. In addition, we observed some modulation of the power spectrum, owing to residual amplitude modulation in the SLM, as shown in Fig. 4 (inset). Consequently, true phase modulation was not achieved. These difficulties, associated with the pixelization of the filter and the residual amplitude modulation, set limitations on the overall performance. The time needed for compression was of the order of minutes. The bottleneck of the process was the updating time of the SLM, which was ~500 ms and was limited by the electronics used, so the time needed for a single iteration was ~1 s. We expect that the compression procedure will be significantly faster when faster electronics, together with higher-update-rate SLM's such as ferroelectric liquid-crystal modulators or acousto-optic modulators, are used. Other feedback signals, in particular higher harmonic generation, can be incorporated into our scheme to improve the compression process.

In summary, we have shown experimentally, for the first time to our knowledge, adaptive femtosecond pulse compression of uncharacterized pulses. Efficient compression was achieved by use of a simulated annealing algorithm, with a single-value feedback measurement. This method proved to be robust and capable of handling the general case in which the input pulses are completely uncharacterized or partially characterized. We expect that adaptive compression and shaping will play an important role in the field of ultrafast optics, as the pulses are automatically optimized for a specific task.

References

1. I. D. Jung, F. X. Kärtner, N. Matuschek, D. H. Sutter, F. Morier-Genoud, G. Zhang, U. Keller, V. Scheuer, M. Tilsch, and T. Schudi, Opt. Lett. **22,** 1009 (1997).
2. M. Nisoli, S. De Silvestri, O. Svelto, R. Szipöcs, K. Ferencz, Ch. Spielmann, S. Sartania, and F. Krausz, Opt. Lett. **22,** 522 (1997).
3. A. Baltuska, Z. Wei, M. S. Pshenichnikov, and D. A. Wiersma, Opt. Lett. **22,** 102 (1997).
4. E. B. Treacy, IEEE J. Quantum Electron. **5,** 454 (1969).
5. R. L. Fork, O. E. Martinez, and J. P. Gordon, Opt. Lett. **9,** 150 (1984).
6. R. L. Fork, C. H. B. Cruz, P. C. Becker, and C. V. Shank, Opt. Lett. **12,** 483 (1987).
7. R. Szipöcs, K. Ferencz, C. H. Spielmann, and F. Krausz, Opt. Lett. **19,** 201 (1994).
8. D. Meshulach, D. Yelin, and Y. Silberberg, Opt. Commun. **138,** 345 (1997).
9. A. M. Weiner, Prog. Quantum Electron. **19,** 161 (1995).
10. W. S. Warren, H. Rabitz, and M. Dahleh, Science **259,** 1581 (1993).
11. F. Krausz, Ch. Spielmann, T. Brabec, E. Wintner, and A. J. Schmidt, Opt. Lett. **17,** 204 (1992).
12. A. M. Weiner, D. E. Leaird, J. S. Patel, and J. R. Wullert, Opt. Lett. **15,** 326 (1990); IEEE J. Quantum Electron. **28,** 908 (1992).
13. M. M. Wefers and K. A. Nelson, Opt. Lett. **20,** 1047 (1995).