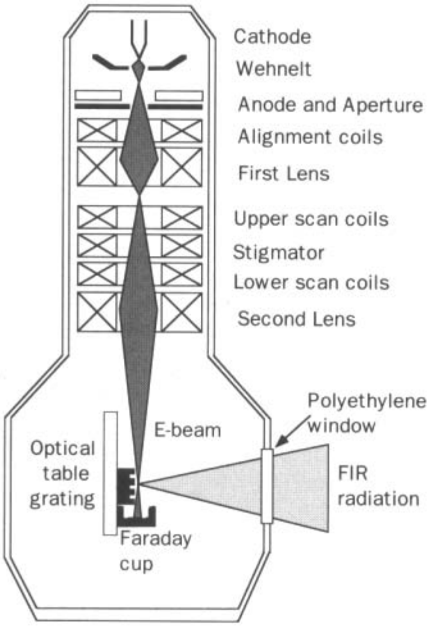


Walsh Figure 1. Schematic of the modified SEM.

vidual electrons constitute a spontaneous emission or shot noise process. In this limit, the essential radiative mechanism is the same as the coupling underlying observations discussed by Smith and Purcell[2] and suggested by Salisbury.[3] The wake of an individual electron consists of not only the radiative components, but also space harmonics, some of which have phase velocities near and slightly below the velocity of the beam electrons. When the beam current density is high enough and the energy spread and emittance of the beam are low, as can be in the SEM, the electron beam bunches in the retarding phase of the near synchronous space harmonic. Provided other losses are small, a coherent, radiative, surface mode develops. Growth will continue until nonlinear processes lead to saturation. In this limit the power emitted can exceed the shot noise level by many orders of magnitude.

A schematic cross-section of the device is shown in Figure 1. The beam is formed on a tungsten "hairpin" cathode and focused and positioned over the grating using the SEMs internal electron optical system. Distributed feedback on the grating itself provides the energy storage needed to achieve growth of the coherent field.

To date, operation over a wavelength range extending from 200 μm to beyond 1 mm has been achieved. Peak-power levels at the detector are currently in the microwatt range. Stability and the signal-to-noise ratios after the signal passes through either a Martin-Puplett interferometer or a grating spectrometer are well within the range required for spectroscopic experimentation. The detailed theory of the device's operation is still under development, but scaling based on fundamental constraints governing any e-beam driven GCO have already been developed. The predictions support the claim that devices of this type should be capable of providing milliwatt power levels over the entire 10–1000 μm wavelength range.

References

1. J. Urata *et al.*, "Superradiant Smith-Purcell emission," Phys. Rev. Lett. **80**, 516 (1998).
2. S.J. Smith and E.M. Purcell, "Visible light from localized surface charges moving across a grating," Phys. Rev. **92**, 1069 (1953).
3. W.W. Salisbury, U.S. Patent 2,634,372 (1953).

ULTRAFAST

Frequency-resolved Optical Gating Characterization of 4.5-fs Pulses

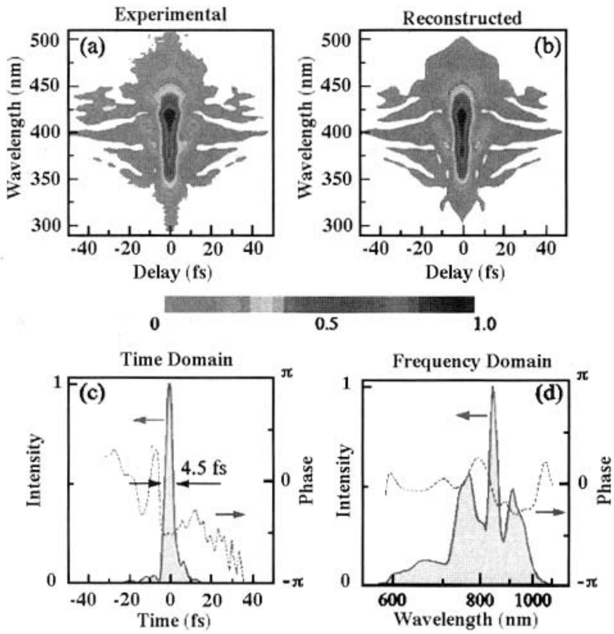
Andrius Baltuška, Maxim S. Pshenichnikov, Douwe A. Wiersma, Ultrafast Laser and Spectroscopy Laboratory, Dept. of Chemistry, Univ. of Groningen, Groningen, The Netherlands.

Accurate phase and amplitude characterization of sub-5-fs laser pulses, which became available a year ago,[1, 2] is essential for most spectroscopic applications. For such short pulses, spectral phase corrections must be carried out across the bandwidth of several hundreds of nanometers. Therefore, a comprehensive knowledge of phase distortions is invaluable for optimization of multistage compressors to obtain the ultimate spectral-limited pulses.

It is well known that frequency-resolved optical gating (FROG)[3] allows unambiguous retrieval of both amplitude and phase of ultrashort pulses. Furthermore, FROG technique uses the geometry of a standard nonlinear optical experiment, which is ideally suited for characterization and on-target optimization of ultrashort pulses that experience dispersive broadening even due to propagation through air. We have recently demonstrated second-harmonic-generation (SHG) FROG characterization of 4.5-fs, 15-nJ fiber-compressed pulses from a cavity-dumped Ti:sapphire laser.[4]

The SHG FROG measurement of sub-5-fs pulses presents a considerable challenge. The main experimental difficulties result from the geometrical time-smearing due to non-collinear geometry and the limited phase matching bandwidth of the nonlinear crystal.[5] We have shown[4] that the effect of geometrical broadening in the case of 5-fs pulses amounts to less than 5% of the duration, provided the experimental geometry is carefully chosen. To estimate the influence of the phase matching conditions, we performed numerical simulation of FROG traces using the full expression for the FROG signal. The results convincingly demonstrate that despite the ultrabroad bandwidth of 5-fs pulses, the signal can still be presented as a product of an ideally phase-matched FROG and a spectral filter that originates from the finite conversion bandwidth due to phase matching. Therefore, the FROG traces of even 5-fs pulses can be readily corrected for the SHG crystal phase mismatch. This fact is of great importance since both conventional FROG retrieval routines and internal consistency checks to validate the experimental data are based on the ideally phase-matched FROG.[3]

Our FROG apparatus is a non-collinear autocorrelator designed for sub-5-fs pulses, which provides total symmetry of the arms and minimal phase distortion.[4] A 10-μm-thick BBO crystal is used to maximize the usable phase matching bandwidth. Two different Ocean Optics PC1000 plug-in spectrometers with CCD arrays are used to detect the fundamental and SHG spectra. The use of a piezo translation stage in one arm ensured precise actuation of the optical delay. The SHG spectra was taken by incrementing the time delay in steps of



Baltuška Figure 1. Experimentally measured (a) and retrieved (b) SHG FROG traces of 4.5-fs pulses and reconstructed amplitudes and phases in the time (c) and frequency (d) domains. Light gray contours in (c) and (d) show field intensities and dashed lines indicate phases.

0.5 fs. The spectral data was corrected for the spectral response of the spectrometers and SHG conversion efficiency. The acquired 2-D arrays of points were converted into a 128 × 128 matrix and processed by commercially available software (Femtosoft Technologies).

The experimental and retrieved SHG FROG are depicted in Figures 1a and 1b, respectively. The FROG error amounts to 0.004 and corresponds mainly to the measurement noise in the spectral wings. Figures 1c and 1d show the reconstructed intensity and phase in the time and frequency domains. The SHG FROG ambiguity in the time direction was removed by comparing the traces of compressed and intentionally chirped pulses. The obtained pulse duration is 4.5 fs while variations of the spectral phase is less than $\pm \pi/4$ across the whole bandwidth. These results fully confirm our previous analysis based on the interferometric autocorrelation.[1] To the best of our knowledge, the 4.5-fs pulses are the shortest pulses to date that have been completely characterized. We believe that the developed technology can be directly applied to even shorter optical pulses that comprise a single optical cycle.

References

1. A. Baltuška *et al.*, "A compact all-solid-state sub-5-fs laser," Opt. & Phot. News **8** (12), 46 (1997).
2. Ch. Spielmann *et al.*, "Ti:sapphire laser produces intense sub-5-fs pulses," Laser Focus World **33** (5), 127 (1997).
3. I. Walmsley and R. Trebino, "Measuring fast pulses with slow detectors," Opt. & Phot. News **7** (3), 23 (1996).
4. A. Baltuška *et al.*, "Amplitude and phase characterization of 4.5-fs pulses by frequency-resolved optical gating," Opt. Lett. **23** (18), 1474–1476 (1998).
5. G. Taft *et al.*, "Measurement of 10-fs laser pulses," IEEE J. of Selected Topics **QE2,** 575 (1996).

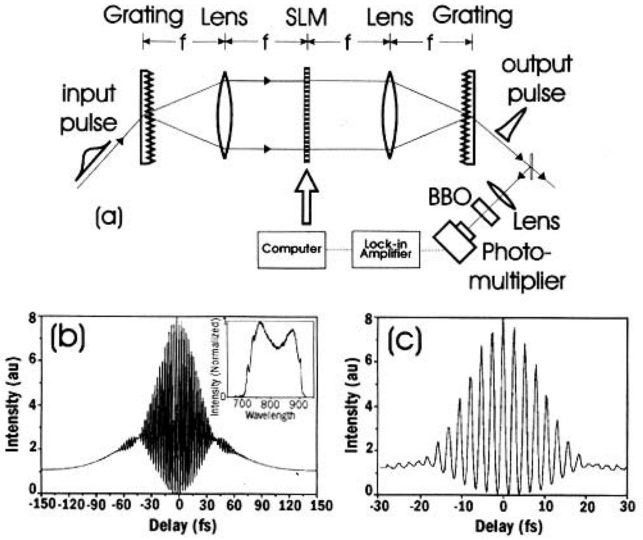
Adaptive Compression and Shaping of Femtosecond Pulses

Doron Meshulach, Dvir Yelin, and Yaron Silberberg, Dept. of Physics of Complex Systems, Weizmann Institute of Science, Rehovot, Israel.

Linearly chirped femtosecond pulses can be compressed efficiently by grating or prism pair compressors. Combination of these compressors can be used to remove slightly more complicated spectral phase distributions. If the spectral phases cannot be approximated by the second- and third-order dispersion terms, or if the pulses are completely uncharacterized, these compressors cannot be used to accomplish efficient compression. Consequently, they cannot be used in situations where pulses undergo slow variations in time.

We have recently demonstrated an adaptive technique that efficiently compresses pulses with unknown arbitrary temporal distortions, even when they vary slowly in time. In this adaptive scheme, the input pulses are compressed iteratively according to feedback measurements of the modified pulses.[1–3] An optimization algorithm uses the feedback signal to modify the pulse shape and to drive it to minimum time duration.

The experimental setup is comprised of a dynamic 4-*f* femtosecond pulse shaper,[4] a feedback measurement device, and a computer(see Fig. 1a). The pulse shaper consists of a pair of thin gratings, a pair of achromatic lenses, and a programmable 1-D liquid crystal spatial light modulator (SLM) array, which was used as an updatable phase-only filter for spectral phase manipulations of the pulses.[2] We used the second-harmonic generation (SHG) signal of the output pulses as the feedback signal, obtained by focusing the pulses onto a thin frequency doubling crystal. In this phase-only filtering, higher-levels of SHG signals correspond to shorter pulses. For opti-



Meshulach Figure 1. (a) Experimental setup for adaptive pulse compression. The SHG of the output pulses was generated using a BBO crystal and detected by a photomultiplier and a lock-in amplifier. (b) Interferometric autocorrelation measurement of uncompressed 80-fs input pulses. (c) Measurement of the output pulses, compressed down to 11 fs after 1,000 iterations.