Single-shot kilohertz characterization of ultrashort pulses by spectral phase interferometry for direct electric-field reconstruction

W. Kornelis, J. Biegert, and J. W. G. Tisch*

Department of Physics, Institute of Quantum Electronics, Swiss Federal Institute of Technology, Zurich, CH 8093, Switzerland

M. Nisoli, G. Sansone, C. Vozzi, and S. De Silvestri

Dipartimento di Fisica, Istituto Nazionale per la Fisica della Materia, Politecnico, Milan, Italy

U. Keller

Department of Physics, Institute of Quantum Electronics, Swiss Federal Institute of Technology, Zurich, CH 8093, Switzerland

Received July 29, 2002

We describe a method of characterizing ultrashort optical pulses that is based on the technique of spectral phase interferometry for direct electric-field reconstruction and is capable of simultaneously measuring the amplitude and the phase of the electric field of a sub-10-fs pulse at kilohertz acquisition rates on a single-shot basis. Use of this technique results in a dramatic increase (>50×) in acquisition rate compared with that of existing diagnostics for full E-field characterization and opens the door to a range of new experiments in which shot-to-shot phase and amplitude fluctuations are studied at kilohertz rates.

OCIS codes: 320.0320, 320.5550, 330.7100, 120.5050, 120.3180.

Complete characterization in amplitude and phase of the electric field—aside from the uncertainty of the carrier envelope offset phase—of an ultrashort pulse down to the few-cycle regime has been demonstrated with several measurement techniques. The most widely used schemes are frequency-resolved optical gating[1] (FROG) and spectral phase interferometry for direct electric-field reconstruction[2,3] (SPIDER), both of which exist in numerous variants. These techniques have been shown to achieve high accuracy, meaning that the reconstructed electric field matches well the physical field of the pulse[4] and high precision,[5] implying a small spread among several reconstructions of the field obtained from the same data. In their original form, FROG and SPIDER measurements are integrated in space and time; thus an average over the spatial mode size and over a large number of shots is usually taken. Both these restrictions have been overcome: a spatially resolved version of SPIDER has been demonstrated,[6] and both FROG and SPIDER have been shown to operate on a single-shot basis but up to now only at low repetition rates of up to 10 Hz.[7]

In this Letter we present a SPIDER setup that is capable of complete single-shot kilohertz characterization of ultrashort laser pulses. With the current generation of chirped-pulse amplification systems operating at kilohertz repetition rates, an important issue is, e.g., the shot-to-shot variation of the pulses in amplitude and phase. Indeed, highly nonlinear processes such as higher-order-harmonic generation[8] are highly sensitive to the electric fields of the amplified ultrashort pulses, and improved knowledge of the electric field of each single driving pulse is imperative for improving our understanding of such processes.

Note that SPIDER requires only the acquisition of two one-dimensional spectra, and, as the reconstruction algorithm is noniterative, it is ideally suited for fast, real-time pulse characterization. To date, the fastest version of SPIDER operates at refresh rates of as much as 40 Hz,[9] but it is not single shot (i.e., it averages over many pulses). For accurate single-shot pulse characterization, simultaneous measurement of both spectra is necessary, as demonstrated in Ref. 10, e.g., by simultaneous measurement of the SPIDER interferogram and of the fundamental spectrum by a single spectrometer. In our setup a separate spectrometer for the fundamental spectrum is used to prevent the distortion that is expected for a broadband spectrum.

We note that SPIDER is insensitive to linear phase variations, and thus the carrier envelope offset phase[11] is undetermined. To completely characterize the electric field of the laser pulse, single-shot and at kilohertz repetition rates, three conditions have to be fulfilled: The fundamental spectrum and the SPIDER interferogram have to be measured (1) independently, (2) simultaneously, and (3) at kilohertz acquisition rates. We satisfy these requirements by using two spectrometers, one for the fundamental spectrum and one for the SPIDER trace, both equipped with fast, dynamically triggerable, line-scan CCD cameras (Basler L101 2k, 10-bit, 2048 pixels) that are capable of frame rates of as much as 9.42 kHz. The two spectrometers are simultaneously triggered from the laser system, ensuring that both acquired spectra belong to the same pulse. The spectrometers are both 0.3-m imaging spectrographs (Acton); they are fitted with a 150- and a 600-line/mm

0146-9592/03/040281-03$15.00/0

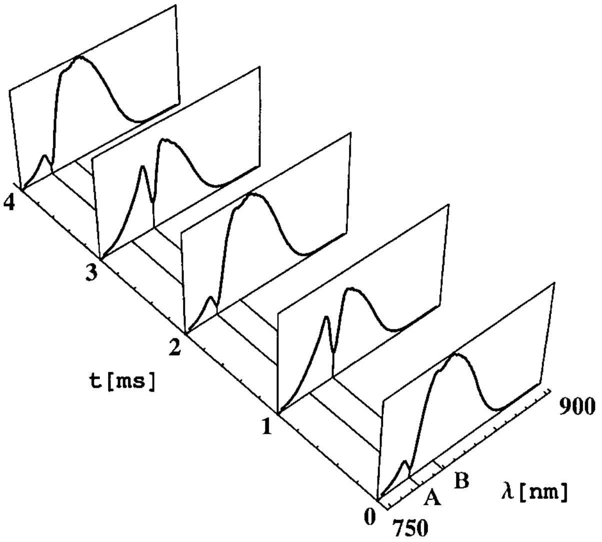

Fig. 1. Measurement taken at 1 kHz of the spectrum of a Ti:sapphire laser for which a spectral hole alternated between two spectral positions ($A = 776$ nm and $B = 799$ nm) at a rate of 500 Hz. The alternation can clearly be seen, thus demonstrating kilohertz acquisition.

grating that give spectral resolutions of 0.5 nm at 800 nm and of 0.1 nm at 400 nm, respectively.

To demonstrate kilohertz operation of our spectrometers, we used an acousto-optic programmable dispersive filter[12] (Dazzler) to introduce an alternating spectral hole (at 500 Hz from 775 to 800 nm) into the fundamental spectrum of a 10-fs Ti:sapphire laser oscillator. Synchronizing the spectrometer with the Dazzler filter and acquiring at a rate of 1 kHz clearly reveal the alternation. Figure 1 shows that the same spectral feature repeats every second frame, a conclusion that is supported by an additional Fourier analysis of a large data set that clearly showed the expected 500-Hz signature. Further careful testing ensured coincidence of the two spectra for each laser shot.

To obtain an estimate of the required laser pulse energy we characterized laser pulses from a Ti:sapphire oscillator (12 fs, 90 MHz, 500 mW). Increasing the acquisition rate resulted in decreasing the signal-to-noise ratio of our measurement until a minimum signal-to-noise ratio for accurate and precise pulse characterization was reached at a 300-Hz acquisition rate. This procedure yielded an approximate value for the necessary pulse energy of 170 nJ. The estimate is conservative because it does not take into account the power scaling of the upconversion efficiency in the crystal; i.e., the minimum energy required will be reduced for shorter pulses. Single-shot kilohertz operation thus requires pulse energies of at least several hundred nanojoules. Optical damage in the nonlinear crystals limits the maximum pulse energy, which in turn limits the maximum acquisition rate. To demonstrate single-shot kilohertz operation, we used a Ti:sapphire chirped-pulse amplification system that delivered sub-25-fs pulses with energies of several hundred microjoules at a repetition rate of 1 kHz. The amplified pulses were focused into a 500-μm-diameter, 60-cm long hollow fiber filled with argon, where they spectrally broadened by self-phase modulation. A combination of chirped mirrors was then used to compress the spectrally broadened pulses to below 10-fs duration.[13,14]

As a first demonstration of the potential of our kilohertz SPIDER, we measured shot-to-shot variations in the pulse's spectral phase and FWHM pulse duration. For this demonstration 10,000 successive pulses were measured at 1 kHz, corresponding to an acquisition period of 10 s. The acquisition period is limited only by the data storage capacity because the data rates

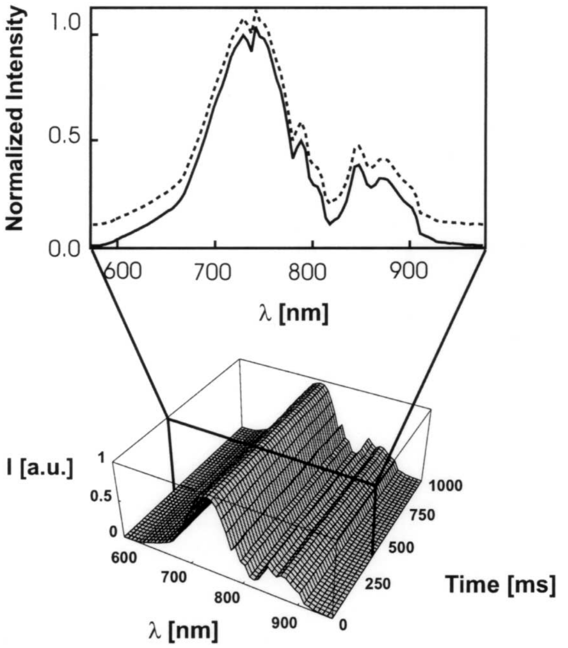

Fig. 2. Fundamental spectrum of the first 1000 shots as a function of wavelength. The two curves display two consecutive shots; the dashed curve has been shifted.

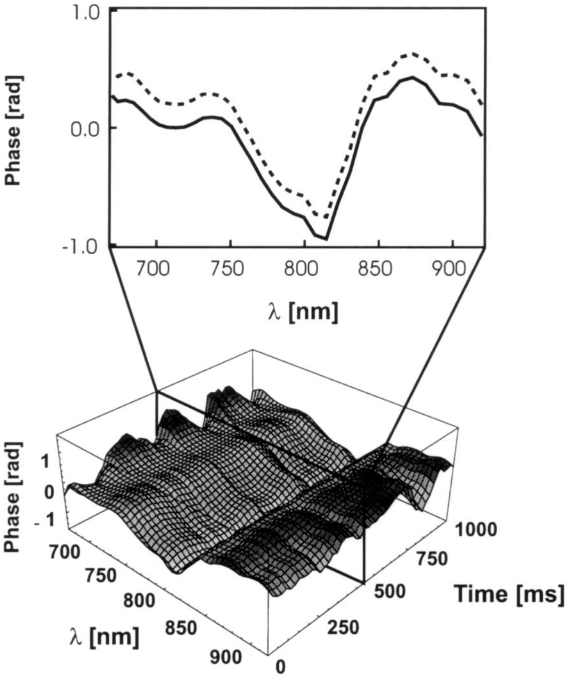

Fig. 3. Spectral phase of the first 1000 shots as a function of wavelength. The two-dimensional figure displays two consecutive shots; the dashed curve has been shifted.

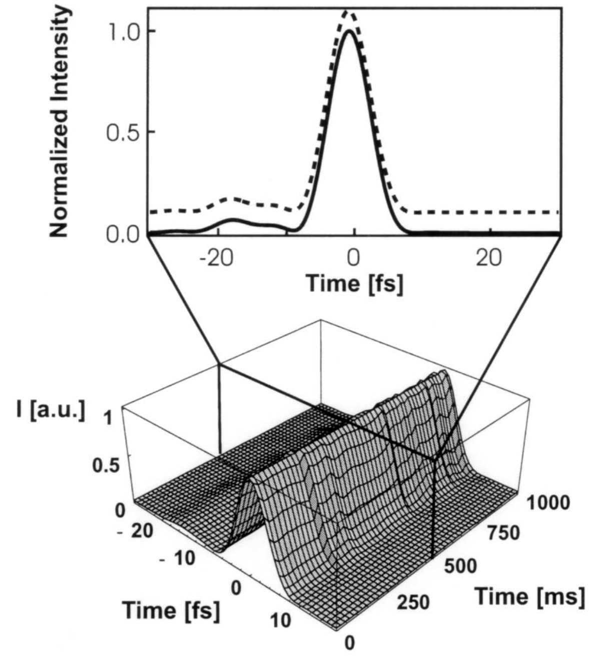

Fig. 4. Reconstructed temporal intensity profile of the first 1000 shots. The curves show two consecutive shots; the dashed curve has been shifted.

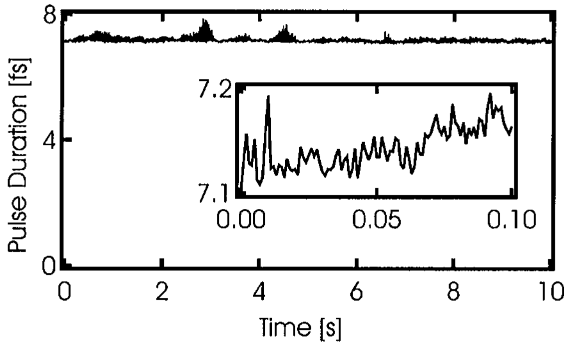

Fig. 5. Time series of 10,000 shots of the FWHM pulse duration. Inset, the same plot for the first 100 shots on a magnified vertical scale.

can easily be handled by modern PCs. In Figs. 2, 3, and 4 the fundamental spectrum, the spectral phase, and the pulse intensity profile, respectively, are plotted as functions of measurement time for 1000 shots. The two-dimensional cuts show two consecutive pulses. Figure 5 shows the FWHM pulse duration of the temporal intensity profile for 10,000 shots; the inset shows the first 100 shots. The phase is found to be reasonably flat, and the FWHM pulse duration averaged over the whole data set is 7.18 fs, which is close to the transform limit of 6.9 fs and in good agreement with a separate interferometric autocorrelation measurement. The pulse durations of all the shots are contained within a range of 7.07–7.85 fs. This small range indicates that the stability in FWHM pulse duration is remarkable for hollow-fiber compressed pulses.

We have demonstrated, for the first time to our knowledge, complete kilohertz single-shot characterization of few-cycle laser pulses by use of SPIDER. As a result of this research it now becomes possible to study in great detail shot-to-shot variations of the spectrum, spectral phase, temporal profile, and pulse duration of ultrafast amplified laser pulses at kilohertz repetition rates. Another interesting potential application is phase-sensitive pump–probe spectroscopy, for which the high repetition rate of our SPIDER makes it possible to increase the signal-to-noise ratio of these measurements considerably; with the large data sets that can readily be acquired, statistics can be dramatically improved.

We gratefully acknowledge helpful discussions with L. Gallmann, G. Steinmeyer, and S. Stagira. This research was supported by the Swiss Quantum Photonics National Center of Competence in Research. J. Tisch acknowledges support from the Engineering and Physical Sciences Research Council, UK. This study was partially supported by the European Community's Human Potential Programme under contract HPRN-CT-2000-00133, ATTO, and by the Istituto Nazionale per la Fisica della Materia, Italy, as part of the project "Clusters as nano-environments for laser-induced extreme states of matter and chemical reactions." W. Kornelis's e-mail address is kornelis@phys.ethz.ch.

*Present address, Blackett Laboratory, Imperial College, London, UK.

References

1. R. Trebino, K. W. DeLong, D. N. Fittinghoff, J. Sweetser, M. A. Krumbügel, and B. Richman, Rev. Sci. Instrum. **68,** 1 (1997).
2. C. Iaconis and I. A. Walmsley, IEEE J. Quantum Electron. **35,** 501 (1999).
3. L. Gallmann, D. H. Sutter, N. Matuschek, G. Steinmeyer, U. Keller, C. Iaconis, and I. A. Walmsley, Opt. Lett. **24,** 1314 (1999).
4. C. Dorrer and I. A. Walmsley, J. Opt. Soc. Am. B **19,** 1019 (2002).
5. C. Dorrer and I. A. Walmsley, J. Opt. Soc. Am. B **19,** 1030 (2002).
6. L. Gallmann, G. Steinmeyer, D. H. Sutter, T. Rupp, C. Iaconis, I. A. Walmsley, and U. Keller, Opt. Lett. **26,** 96 (2001).
7. C. Dorrer, B. de Beauvoir, C. Le Blanc, S. Ranc, J.-P. Rousseau, P. Rousseau, and J.-P. Chambaret, Opt. Lett. **24,** 1644 (1999).
8. P. Salières and M. Lewenstein, Meas. Sci. Technol. **12,** 1818 (2001).
9. C. Dorrer and I. A. Walmsley, in *Conference on Lasers and Electro-Optics (CLEO)*, Vol. 73 of OSA Trends in Optics and Photonics Series (Optical Society of America, Washington, D.C., 2002), paper CMR5.
10. C. Dorrer, Opt. Lett. **24,** 1532 (1999).
11. H. R. Telle, G. Steinmeyer, A. E. Dunlop, J. Stenger, D. H. Sutter, and U. Keller, Appl. Phys. B **69,** 327 (1999).
12. F. Verluise, V. Laude, J.-P. Huignard, P. Tournois, and A. Migus, J. Opt. Soc. Am. B **17,** 138 (2000).
13. M. Nisoli, S. De Silvestri, and O. Svelto, Appl. Phys. Lett. **68,** 2793 (1996).
14. M. Nisoli, S. De Silvestri, O. Svelto, R. Szipocs, K. Ferencz, C. Spielmann, S. Sartania, and F. Krausz, Opt. Lett. **22,** 522 (1997).