Temporal characterization of ultrashort high power laser pulses

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ABSTRACT

Full characterization of the electric field amplitude and shape of an ultrashort optical pulse is important for a number of fields of research, such as high-field atomic and plasma physics, and the generation of ultrashort-pulse XUV and soft x-ray radiation. We have used the technique of frequency-resolved optical gating (FROG) to characterize low-energy pulses as short as 13 fs duration, and high peak-power pulses as short as 25 fs. We discuss experimental considerations for implementing FROG for very short pulses, and the limitations of the technique.

Keywords: ultrashort pulses, UV and x-ray sources, phase matching, pulse characterization, FROG

1. MOTIVATION

The recent development of high peak power lasers with pulse duration well under 100 fs [1] has important implications for fundamental studies of laser-matter interactions, and for applications such as the development of new sources of UV and XUV radiation.[2,3] From a fundamental point of view, the interaction of an atom with an optical pulse less than 10 optical cycles in duration (~30fs) represents a new regime, with new physical effects. For example, in recent work, we demonstrated that by simply altering the chip of an incident high-energy laser pulse, the wavelength of the XUV harmonics generated in a low-pressure gas can be tuned.[4] Furthermore, the spectral shape of the harmonics depends on the chirp, in a manner determined by the interaction of the radiating electron wavepacket with an EM field of rapidly varying amplitude and phase. It is clear that, to separate atomic effects from artifacts due to the exact temporal/spectral shape of the laser pulse, a detailed characterization of the driving pulse is necessary on a *cycle-by-cycle* basis. Third harmonic generation in gasses also exhibits a conversion efficiency which optimizes for a non-transform-limited excitation pulse.[5] In many other types of experiments, such as laser-plasma based particle accelerators, a detailed comparison of theory and experiment requires knowledge of the pulse shape. Finally, the use of pulse-shaping techniques will allow us to optimize many of these processes. Characterization of the output is integral to the development of these techniques.

The Frequency Resolved Optical Gating (FROG) technique is a diagnostic tool which provides a full characterization of ultrashort pulses.[6,7] The FROG technique is a general technique which can be applied to a wide variety of pulses (ibid.), but which requires care in implementation. In our work, we found that characterization of near transform-limited pulses both for nanojoule-energy pulses down to 13 fs, and for high-power amplified pulses down to 25 fs, was possible.[8] However, for pulses chirped to more than twice the transform-limited pulse duration, convergence of the required data deconvolution is more difficult. The discrepancies are most apparent when comparing the spectrum of the FROG output with that measured in the lab; disagreements of up to 50% are common. In the work described herein, we identify the source of some of these discrepancies, and suggest possible experimental and computational corrections.

2. EXPERIMENTAL SET-UP AND CONSIDERATIONS

In this work we used a single-shot Second Harmonic Generation (SHG) FROG set-up[9] using a millijoule, kilohertz repetition-rate laser system which generates 20 fs pulses.[10] This technique is experimentally quite similar to a standard single-shot autocorrelator, but the *spectrum* of the second-harmonic autocorrelation signal is measured, rather than simply the signal intensity. The beam was split in a beamsplitter, and the two beams then crossed at a

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small angle (< 5 deg) in a 75 micron KDP crystal. The second-harmonic output was imaged into a CCD array spectrometer for the signal measurement. A full data set consists of a FROG trace for every input laser pulse chirp setting, together with an independent measurement of the spectrum of the input pulse. One of the benefits of the FROG technique, especially SHG FROG, is that the self-consistency of the data can be extensively checked. The temporal marginal (intensity as a function of time delay integrated over frequency of the FROG trace) of a SHG FROG trace should correspond to the autocorrelation of the pulse, while the frequency marginal (intensity as a function of frequency integrated over time delay of the FROG trace) is the mathematical equivalent to an autoconvolution of the power spectrum of the pulse.[6,7,9] While we have rarely had problems matching the temporal marginal to our autocorrelation data, we should note that this test is not a totally independent one unless the autocorrelation is taken with a different experimental set-up than that for the SHG FROG measurement. The frequency marginal comparison, however, *is* an independent test and has proven to be a very useful comparison for finding experimental problems, especially for the case of chirped pulses. As the chirp of the input pulse was varied, the frequency marginal peak would sometimes shift or broaden. Since the spectrum of the pulse does not change with chirp, this implies that the data were no longer self-consistent.

We found that two adjustments were important to obtain the best possible frequency marginal comparison. First, it is important to carefully adjust the phase matching of the crystal to obtain best agreement and *not* simply to optimize the signal intensity. We found that, typically, the best marginal agreement occurs in the case when the crystal is tuned towards longer wavelengths. This was due to the broader phase-matching bandwidth for KDP in this case, which is an important consideration for our ultrashort, broad bandwidth (up to 150 nm FWHM) pulses. The finite bandwidth of the phase matching can in principal be included in the deconvolution, but since the exact orientation of the crystal is unknown in practice, this is difficult in practice. The second and most sensitive factor for good data acquisition is to carefully adjust the overlap of the two beams in the crystal, so that the same part of the cross-section of the pulse is used from both beams. The data seem sensitive to slight differences in divergence or non-linear effects between different parts of the beam. Experimentally, we found that the adjustment corresponding to best frequency-marginal agreement corresponded to exact physical overlap of the beams in the crystal, and that the marginal comparison was a much more sensitive measure of this overlap than simply directly observing the beam overlap directly on the crystal.

The FROG measurement is also very sensitive to any spatial chip on the beam, which can result from a misadjusted stretcher/compressor system. FROG traces can be useful for detecting such a chirp, but the measurement is complicated by the above mentioned factors. In general, observing the spectrum of the pulse at different parts of the beam is a prerequisite to attempting a careful FROG measurement.

3. RESULTS

After addressing and correcting all of the above mentioned problems, reliable pulse reconstructions are possible even for non-transform-limited pulses. Figure 1 shows a representative data set, illustrating the pulse shape as a function of the position of the compressor grating (corresponding to the chirp of the pulse). Figures 1a, 1c, and 1e show the electric fields in time while 1b, 1d, and 1f show the spectra which correspond to those fields compared with the independently measured spectrum. Figures 1a and 1b are for the transform-limited case, where the pulse shape is very regular and the spectrum of the reconstructed pulse matches the observed spectrum. The temporal phase is very flat in the region where the data has good signal to noise. For figures 1c through 1f, the number labeling each curve is the difference in compressor grating separation from the position corresponding to the transform-limited case. In this set of data, we were primarily interested in whether the chirped pulse might develop a temporal substructure that could have an effect on harmonic generation. These data indicate that there is no structure, but some difference in pulse rise time for negative chirp compared with positive chirp. In figure 2, we show the frequency marginal comparisons for all six settings of the compressor. It is clear that the data set is self-consistent based on this marginal comparison. After making the corrections to our experimental set-up, we found that we got 50% better convergence with this data set than for similar measurements made on this system in the past.

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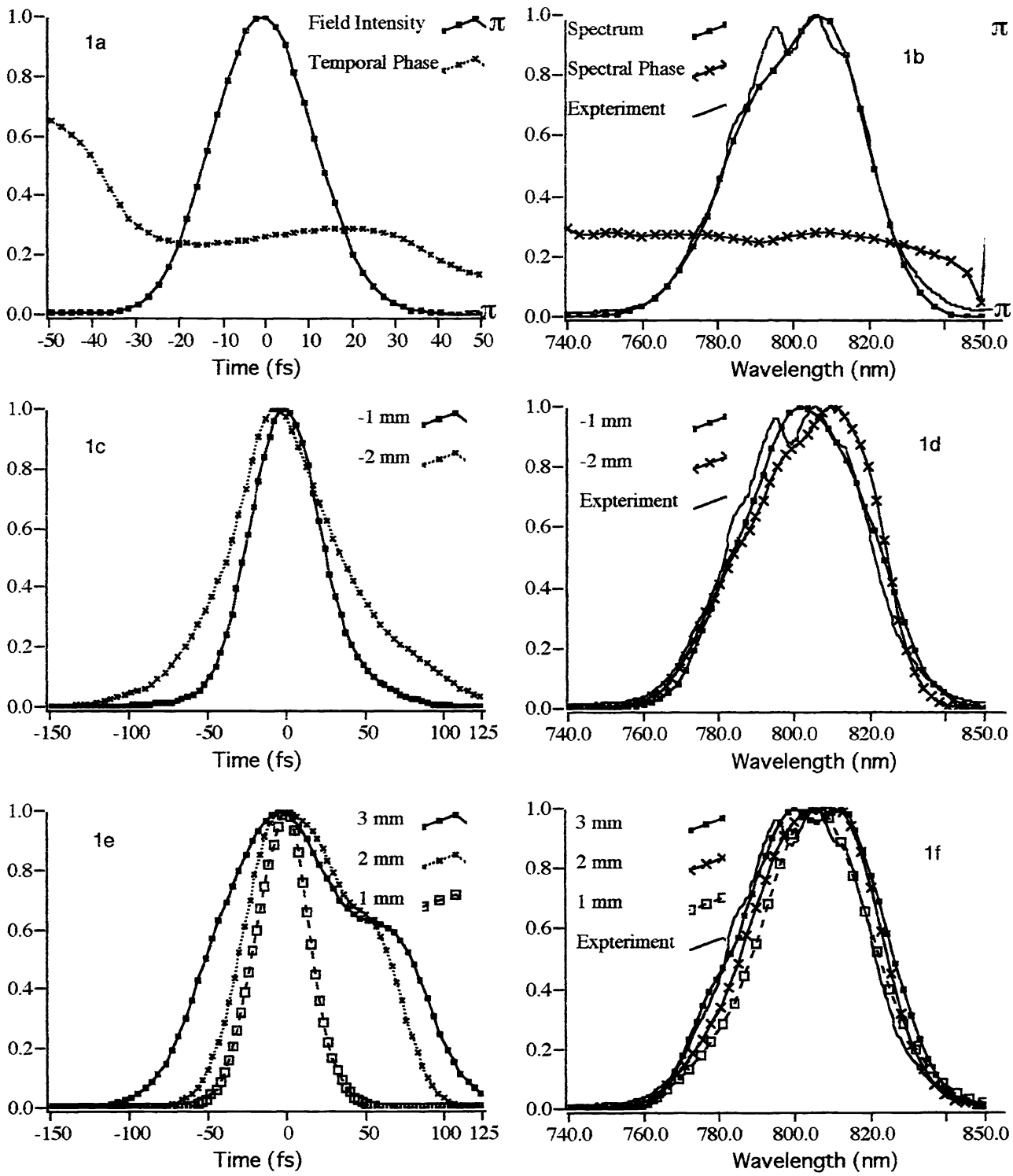


Fig. 1. Retrieved electric fields and spectra as a function of compressor grating separation (compared with transform-limited separation).

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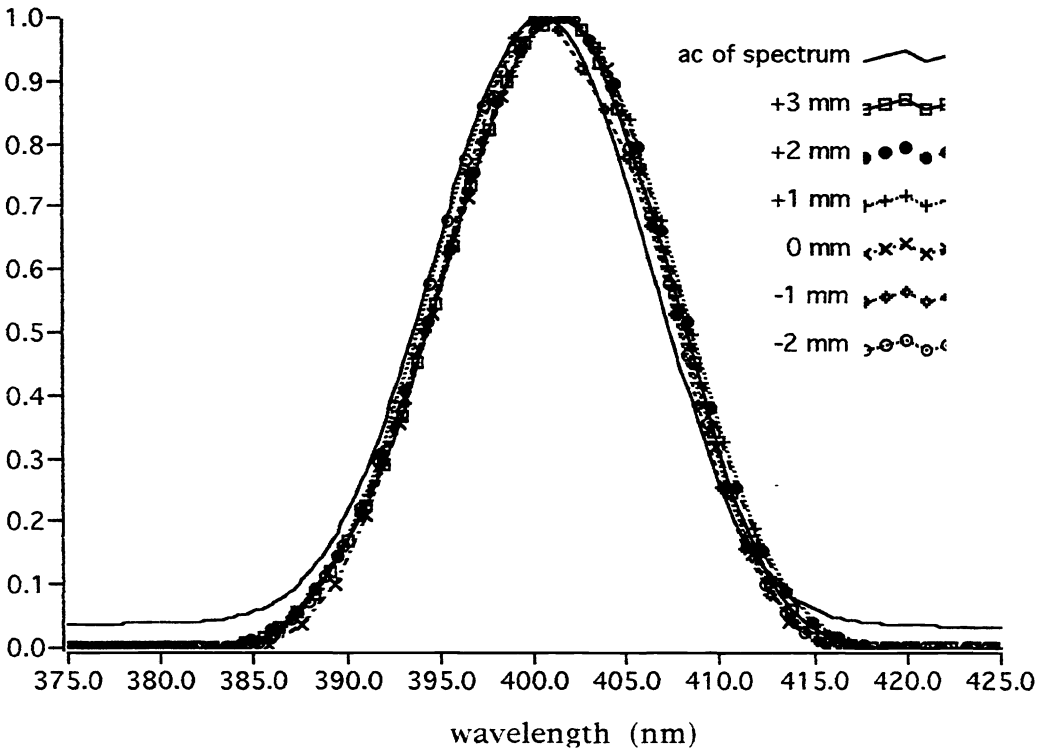


Fig. 2. Frequency marginals of six FROG traces compared to the autoconvolution of the fundamental spectrum.

4. CONCLUSIONS

We have performed the first full characterization of 25 fs amplified pulses which can be used for detailed comparison of experiment with theory in high-field laser-matter interactions. We have also verified the reliability of the FROG technique for high peak-power ultrashort pulses, and have discussed several experimental considerations to be dealt with when attempting this measurement.

5. ACKNOWLEDGMENTS

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