Single-shot TG FROG for the characterization of ultrashort DUV pulses

Tamas Nagy* and Peter Simon

Laser-Laboratorium Göttingen e.V., Hans-Adolf-Krebs-Weg 1, 37077 Göttingen, Germany
**tamas.nagy@llg-ev.de*

Abstract: A single-shot all-reflective transient grating (TG) FROG arrangement is presented for the full characterization of DUV pulses of ps to a few fs duration. The performance of the device is demonstrated by experimental data measured on KrF lasers of different pulse durations.

OCIS codes: (320.0320) Ultrafast optics; (320.7100) Ultrafast measurements.

References and links

1. P. Baum, S. Lochbrunner, and E. Riedle, "Tunable sub-10-fs ultraviolet pulses generated by achromatic frequency doubling," Opt. Lett. **29**(14), 1686–1688 (2004).
2. C. G. Durfee III, S. Backus, H. C. Kapteyn, and M. M. Murnane, "Intense 8-fs pulse generation in the deep ultraviolet," Opt. Lett. **24**(10), 697–699 (1999).
3. T. Fuji, T. Horio, and T. Suzuki, "Generation of 12 fs deep-ultraviolet pulses by four-wave mixing through filamentation in neon gas," Opt. Lett. **32**(17), 2481–2483 (2007).
4. U. Graf, M. Fieß, M. Schultze, R. Kienberger, F. Krausz, and E. Goulielmakis, "Intense few-cycle light pulses in the deep ultraviolet," Opt. Express **16**(23), 18956–18963 (2008).
5. S. Szatmari, "High-Brightness Ultraviolet Excimer Lasers," Appl. Phys. B **58**, 211–223 (1994).
6. T. Nagy and P. Simon are preparing a manuscript to be called "Generation of 200-μJ, 25-fs DUV pulses using a hollow-fiber compressor".
7. R. Trebino, *Frequency-Resolved Optical Gating: The Measurement of Ultrashort Laser Pulses* (Kluwer Academic Publishers, 2002).
8. M. Li, J. P. Nibarger, C. L. Guo, and G. N. Gibson, "Dispersion-free transient-grating frequency-resolved optical gating," Appl. Opt. **38**(24), 5250–5253 (1999).
9. D. Lee, S. Akturk, P. Gabolde, and R. Trebino, "Experimentally simple, extremely broadband transient-grating frequency-resolved-optical-gating arrangement," Opt. Express **15**, 760–766 (2007).

1. Introduction

The development of ultrashort DUV light sources has recently gained considerable interest because of many potential applications such as femtochemistry, time-resolved spectroscopy, x-ray generation, micromachining or holography.

Basically, there are two different approaches for the generation of ultrashort pulses in the DUV. One approach is to directly convert few-cycle IR pulses to the UV with some ultra-broadband frequency conversion scheme such as non-collinear achromatic phase matching in nonlinear crystals [1], or four-wave mixing in hollow fibers [2,3], or harmonic generation in gas jets [4]. These light sources deliver weak (some μJ) sub-30 fs pulses at high repetition rates (kHz range). For these lasers a sensitive multiple-shot measurement device is best suited.

The majority of DUV light sources however, follow a different approach. In these systems the frequency converted moderately short pulses are amplified in an ArF (193 nm) or in a KrF (248 nm) excimer module [5]. These devices operate at low repetition rates (up to 10 Hz), they have moderately short pulses (sub-ps to 100 fs) but a high pulse energy (several 10 mJ) and a large flat-topped beam profile. Recently, the operation range of this class of lasers has been extended to pulse durations below 30 fs maintaining high pulse energies (several 100 μJ) by applying the hollow fiber compression technique to the output of a KrF amplifier [6]. For these sources single-shot measurement devices are best suited, but up to now only multiple-shot autocorrelators have been available.

Currently the only way to fully characterize DUV pulses is to use a FROG arrangement incorporating third-order nonlinearity such as polarization gating (PG), self diffraction (SD) or the transient grating (TG) effect, since all other methods either do not give phase

#109383 - $15.00 USD Received 30 Mar 2009; revised 17 Apr 2009; accepted 23 Apr 2009; published 29 Apr 2009

information or involve additional frequency conversion, which is not feasible in the DUV [7]. In order to be able to measure sub-100 fs pulses, only all-reflective schemes can be considered because of the high material GVD in this spectral range. In this sense the amplitude splitting arrangements and the PG scheme rule out. In order to reach ultimate temporal resolution, the TG scheme is the method of choice, while its spectral filtering effect is considerably smaller than that of the SD scheme, which is a particularly important issue in the UV. Furthermore, the SD arrangement is not fully phase matched like the TG arrangement therefore its sensitivity is not as high as that of the TG scheme. Based on the above arguments, a single-shot all-reflective TG FROG arrangement is considered as the best choice for versatile use for pulse characterization in the DUV range. Although all necessary techniques have already been developed, to date no such device exists. A multiple-shot dispersion-free TG FROG was proposed by Li et al. [8]. Based on this scheme Lee et al. developed a single-shot TG FROG [9], although it contained transmission optics. From a geometrical optical point of view the on-axis arrangement in [9] is fully correct, but because of the material GVD the transmission optics introduce variable chirp across the beam profile. This effect can be neglected in the visible and IR spectral range, but it is crucial in the DUV. Our intention was to combine the advantages of the above approaches and find an all-reflective single-shot arrangement which enables the measurement of ultrashort DUV pulses.

2. Geometrical issues

Since an on-axis arrangement is hard to realize by reflective optics, an off-axis focusing geometry is necessary. Two effects of the off-axis geometry have to be considered: i) the caustic of the cylindrical lens will introduce an asymmetrical distortion which leads to broadening of the focal line resulting in a slight loss of sensitivity, and ii) the optical path length across the beam profile will vary, leading to a nonzero time delay between the beamlets emerging from different areas of the original beam profile. These beamlets have to be synchronous, since any time delay between them would yield a smaller measured value for the pulse duration than it is in reality. Therefore this effect has to be carefully investigated.

The focusing geometry of a cylindrical mirror is showed in Fig. 1.

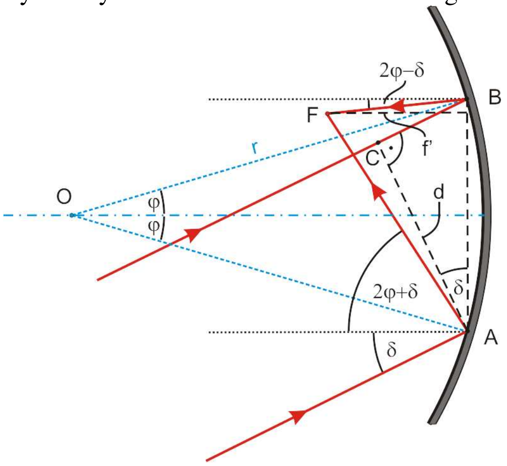

Fig. 1. Off-axis focusing geometry of a cylindrical mirror.

Two rays with a separation of d are falling symmetrically on a cylindrical mirror with a radius of curvature (RoC) of r at an angle of δ, resulting in an average overall beam deflection of 2δ. The lower ray propagates along $\overline{AF}$ while the upper ray along $\overline{CB}$ and $\overline{BF}$ before they intersect at F. Therefore the path difference is $\Delta = \overline{AF} - \overline{CB} - \overline{BF}$, where

$$\overline{AF} = \frac{f'}{\cos\left(2\phi + \delta\right)}, \tag{1}$$

$$\overline{CB} = d \tan \delta, \tag{2}$$

$$\overline{BF} = \frac{f'}{\cos\left(2\phi - \delta\right)} \tag{3}$$

and

$$f' = \frac{d}{\cos \delta \left[\tan\left(2\phi + \delta\right) + \tan\left(2\phi - \delta\right) \right]}. \tag{4}$$

The angle φ can be calculated according to

$$\sin \phi = \frac{d}{2r \cos \delta} \tag{5}$$

From Eqs. (1)-(5) the path difference and therefore the time delay between the rays can be computed. The results of the calculation show that it is possible to find practical sets of parameters (see Table 1) resulting in negligible time delays between the regarded rays.

3. Arrangement

The layout of the FROG arrangement is shown in Fig. 2. An input mask with three rectangular holes arranged at the corners of a rectangle acts as a beam splitter. The three beamlets emerging from the mask (M) are focused by a vertically oriented cylindrical mirror (CM) which is slightly tilted horizontally. The converging beamlets are reflected with a retro-reflector, whose upper element consists of two mirrors (SM) enclosing an angle of Θ. The back-reflected beams are made to overlap in the focus of the cylindrical mirror where a thin fused silica substrate is placed, serving as the nonlinear medium (NLM). Because the pulse fronts of the crossed beamlets are tilted relative to each other, the time delay between the pulses changes linearly along the line focus enabling single-shot detection.

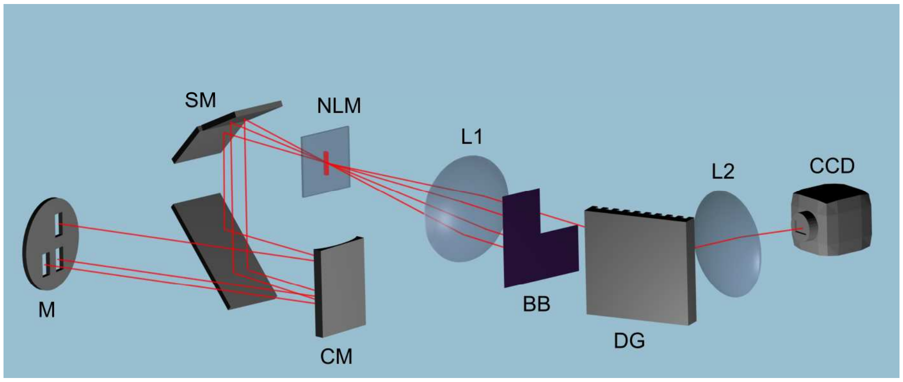

Fig. 2. The single-shot all-reflective TG FROG arrangement. (For the labels see text.)

Although the TG arrangement is fully phase-matched, a thin medium is used in order to keep the material GVD negligible during the nonlinear process. The beam generated by the nonlinearity emerges at the fourth corner of the virtual rectangle. Behind the autocorrelator, similar to [9], a very simple transmission imaging spectrograph is located whose entrance slit is formed by the line focus of the cylindrical mirror in the nonlinear medium. A diffraction grating (DG) is placed between two large-aperture spherical lenses (L1 and L2) which image the line focus onto a UV-sensitive camera (CCD). Both lenses are aligned in a way that their

#109383 - $15.00 USD Received 30 Mar 2009; revised 17 Apr 2009; accepted 23 Apr 2009; published 29 Apr 2009

optical axes coincide with the optical axis of the full beam profile formed by the four beamlets. This alignment ensures that the images of the entrance slit created by each diffraction order of the grating are parallel to each other, which is necessary for a precise alignment of the spectrometer. A beam block (BB) is placed in front of the grating transmitting only that beamlet which is created by the nonlinear interaction.

In order to meet the requirements of both very short (sub-10 fs) and rather long (sub-ps) pulses, two devices were built incorporating the same scheme shown in Fig. 2 with different parameters, listed in Table 1.

Table 1. Key parameters of the two FROG devices

	Standard FROG	**High-resolution FROG**
Pulse duration range	100 fs – 1 ps	sub-10 fs – 100 fs
Full time window	4.1 ps	437 fs
Spectral inspection range	13.5 nm	28.2 nm
Temporal mismatch	1.40 fs	0.084 fs
Size of a single beamlet	2 mm x 7 mm	2 mm x 3 mm
Max. hor. ray separation (d)	7 mm	7 mm
Off-axis angle (δ)	8.5°	2.16°
RoC of the cyl. mirror (r)	250 mm	508 mm
Full crossing angle (Θ)	10°	2.5°
Nonlinear medium	0.2 mm fused silica	0.05 mm fused silica
Focal length of L_1	200 mm	275 mm
Grating density	2400 l/mm	600 l/mm
Focal length of L_2	200 mm	500 mm

In order to keep the throughput of the device as high as possible, highly reflective dielectric mirrors are used in both setups. The ~20 nm reflection bandwidth of the mirrors can handle pulses down to 5 fs duration without spectral clipping or modulation. No evidence of any dispersive effect due to the layer structure of the coating was recognized during the measurements (see next section).

The pixel dispersion of the devices was calibrated by an air-spaced Fabry-Perot etalon having a separation of 50 μm. The absolute position of the spectral axis was determined by recording the fine structures in the spontaneous emission of a KrF excimer laser and the temporal axis was calibrated by recording a double-pulse signal generated by a Michelson interferometer. We note that by rotating the entrance aperture by 180 degrees makes one of the pump beams propagate into the original direction of the nonlinear signal, turning the FROG device into a simple spectrograph. It enables a convenient adjustment and calibration of the spectrograph.

4. Experiments

The single-shot operation of the DUV FROG devices is demonstrated by measuring KrF laser pulses of different pulse lengths at 248 nm. In each measurement a frame of background noise was recorded and subtracted from the measured trace. The most effective way of generating a proper background frame was to block one input beamlet which is located opposite to the signal beam. The FROG code of Femtosoft Technologies was used for data retrieval.

4.1 Standard FROG for 100 fs to 1 ps pulse duration

The compressed output of a Ti:Sapphire – KrF excimer laser system delivering ~20 mJ pulses in a smooth, nearly flat-topped beam profile of ~40x25 mm^2 with a duration of 100-120 fs at 5 Hz was attenuated and measured (see Fig. 3). The FROG error for the 128x128 trace was 0.36%, which is remarkably low.

#109383 - $15.00 USD Received 30 Mar 2009; revised 17 Apr 2009; accepted 23 Apr 2009; published 29 Apr 2009

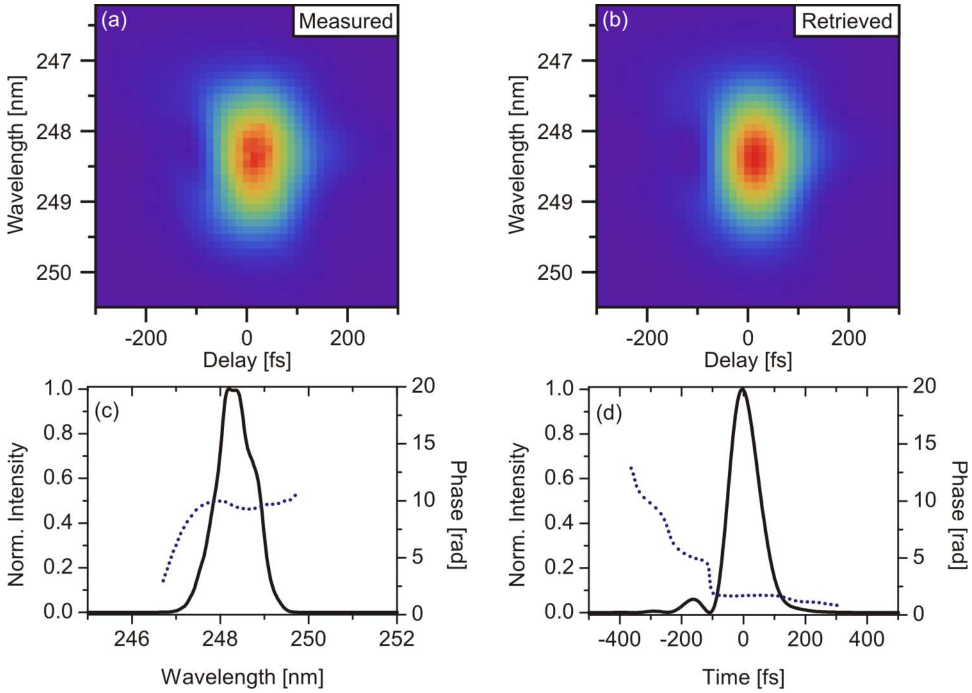

Fig. 3. Single-shot FROG measurement of a transform-limited 110-fs DUV pulse. The measured (a) and retrieved (b) FROG traces, and the retrieved spectral (c) and temporal (d) profiles of the pulse are displayed.

Since the pulse duration was close to the lower limit of the device, only a small portion of the beam profile contributed to the trace. In order to test the parallelism of the line foci a longer pulse was also characterized by the device. In this case a 20-cm-long water cell was placed between the seed pulse generator and the KrF amplifier in order to stretch the pulse duration by material dispersion. The traces are shown in Fig. 4 showing a positively chirped pulse of 1.3 ps pulse duration (FWHM). The FROG error of the 256x256 trace was 1.0%. The somewhat higher error is accounted for the slight clipping of the signal's tail at one end of the time window (see the lower left part of the trace). The vertical stripes on the experimental trace are caused by the aberrations due to the surface imperfections of the thin fused silica plate.

#109383 - $15.00 USD Received 30 Mar 2009; revised 17 Apr 2009; accepted 23 Apr 2009; published 29 Apr 2009

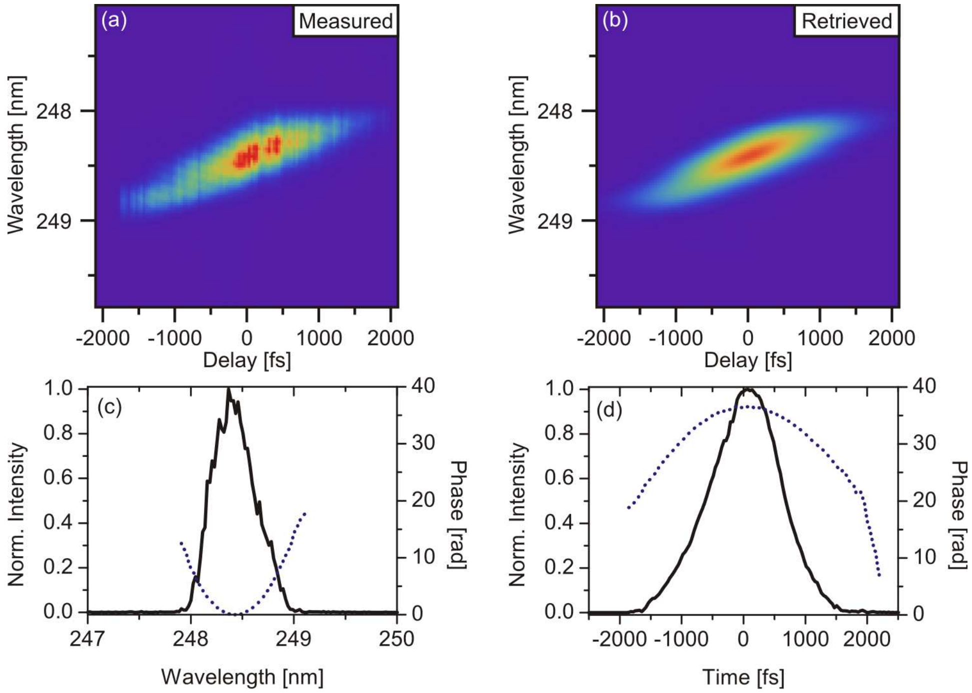

Fig. 4. Single-shot FROG measurement of a positively chirped 1.3-ps DUV pulse.

To show the ability of the device to characterize complex pulses, the output of a Michelson interferometer was measured (Fig. 5). The error of the 512x512 trace was 0.38%.

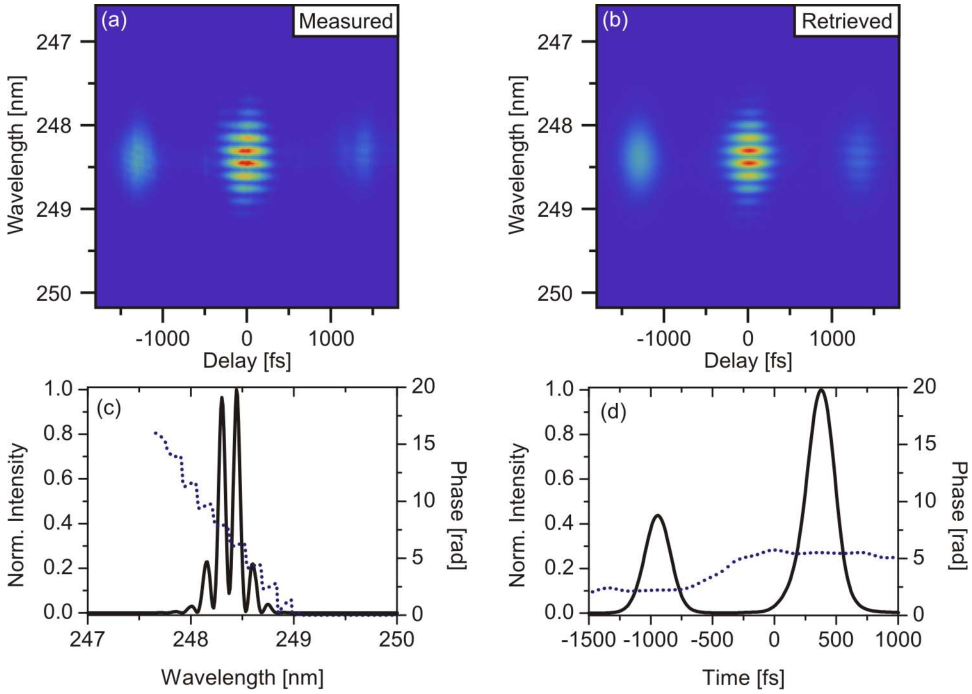

Fig. 5. Single-shot FROG measurement of a double-pulse structure.

#109383 - $15.00 USD Received 30 Mar 2009; revised 17 Apr 2009; accepted 23 Apr 2009; published 29 Apr 2009

In all the above cases the pulse energy in the ~18 mm diameter input beam which filled the input mask of the device was adjusted to be between 300 μJ and 400 μJ, which is regarded as the optimal operation range of the device. A set of measurements was also carried out to explore the detection limit of the device by gradually attenuating the input pulses of ~160 fs duration. At maximal camera gain a pulse of ~50 μJ energy produced an error of ~1% for a 128x128 trace which was already determined by the camera noise. This value is considered as the lower limit of the measurable pulse energy by this device.

4.2 High-resolution FROG for sub-10 fs to 100 fs pulse duration

The performance of the high-resolution FROG device was tested recently by measuring the compressed output of a neon-filled hollow-fiber arrangement used to broaden the spectrum of KrF laser pulses [6], carrying an energy of ~150 μJ in a clean Gaussian-like beam profile. The traces shown in Fig. 6 reveal a complex spectral and temporal structure which is common to spectral broadening due to SPM.

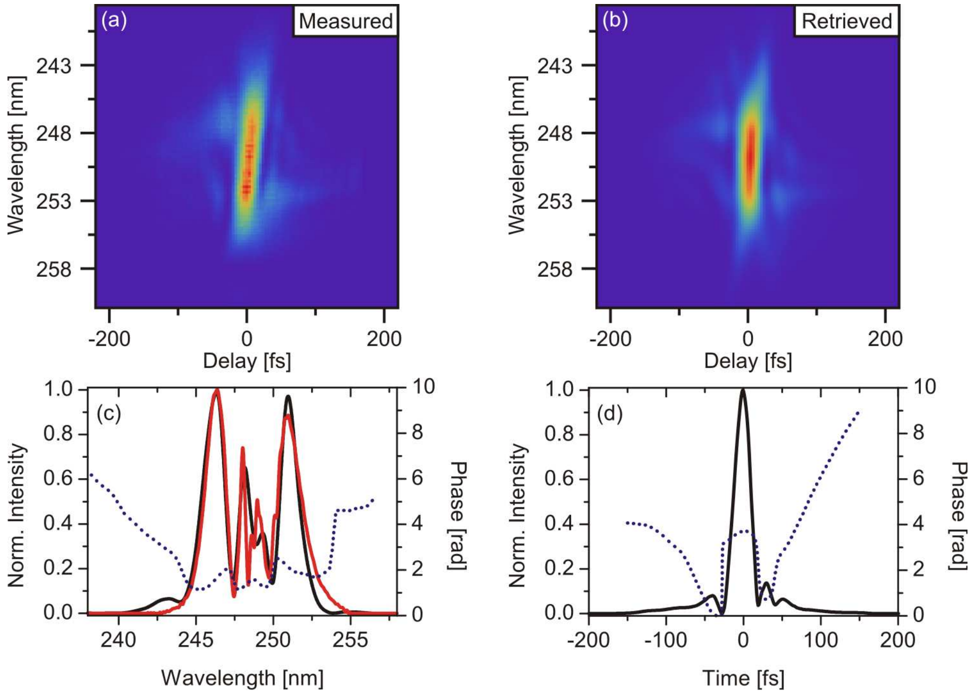

Fig. 6. Single-shot FROG measurement of a 24-fs DUV pulse. The red curve in (c) displays the spectrum recorded by an external spectrograph.

To verify the accuracy of the FROG measurement, the spectrum of the same pulse was measured independently by an external spectrograph whose trace is also indicated in Fig. 6. Although the measured and retrieved spectra are not identical, the agreement between them is good. The FROG error of the 256x256 trace is 1.0% which is to our knowledge one of the best results ever published in this regime.

5. Conclusion

A single-shot all-reflective TG FROG arrangement is proposed for the characterization of ultrashort DUV pulses. In the design critical issues characteristic of the deep-UV spectral range are addressed. For the first time, experimental traces demonstrate the single-shot operation from 24 fs to 1.3 ps in the DUV. The arrangement should be able to measure pulses as short as 5 fs but this was not demonstrated because of the lack of such pulses. Although the

#109383 - $15.00 USD Received 30 Mar 2009; revised 17 Apr 2009; accepted 23 Apr 2009; published 29 Apr 2009

arrangement was primarily designed for the challenging task of DUV pulse characterization, it can be easily adapted for the measurements throughout the visible and IR spectral range.

Acknowledgments

The authors would like to thank R. Trebino for his advices given at an early stage of the work.

#109383 - $15.00 USD Received 30 Mar 2009; revised 17 Apr 2009; accepted 23 Apr 2009; published 29 Apr 2009