Fourier domain interferometry for time-resolved optical properties of X-ray-excited states

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Application Note

Abstract
Spectral interferometry, also called Fourier-domain interferometry (FDI) [1], is a well-known linear optical technique for retrieving the phase and the amplitude of an unknown electric field. This technique is now widely used in ultrafast high-intensity laser-matter interaction experiments. We employed this technique to characterize an ultra-fast change in complex refractive index of a material upon X-ray excitation. We characterized the timing jitter between femto-second X-ray free electron laser (XFEL) and the optical laser at the European XFEL facility at the SPB/SFX instrument for the first time [2].

Introduction
Ultra-short, bright XFEL pulses are enabling new areas of science in chemical, physical and biological studies. For example, the ultra-short pulse duration of XFEL – down to a few femtoseconds – allows time-resolved experiments on atomic time-scales [3]. However, shot-to-shot timing jitter of the pump-probe delay, e.g., between the X-ray and optical laser, typically few tens to hundreds femtoseconds [4], can corrupt any benefit of using ultrashort pulse durations if the jitter is not correctly characterized for each pulse. The intrinsic timing jitter of the X-ray beam is mainly due to the stochastic nature of non-seeded self-amplified spontaneous emission (SASE) in the accelerator [5].

Experiment
We performed the pump-probe timing jitter measurement using the so-called spectral encoding method [6] with a Kymera 193i-B2 imaging spectrograph from Andor Technology with 600 lines/mm diffraction grating. Our spectral encoding setup uses a linearly chirped optical laser pulse that spatially and temporally overlaps the XFEL pulse at the sample position. Different spectral components of the chirped optical pulse arrive at the sample at different times providing a direct mapping of wavelength to time. The interaction of an X-ray pulse with the sample leads to a change in its optical properties, providing the change in spectral amplitude at the relative time of arrival. The X-ray photon energy was 10.5 keV with a pulse energy of approximately 800 µJ and duration of 50 fs full width at half maximum (FWHM). A 15 fs Fourier-limited frequency bandwidth with 800 nm central wavelength optical laser pulse was chirped to 12.7 ps duration by inserting a 200 mm Schwerflintglas 57 (SF57) rod. The sample was 10 µm thick $Gd_{2.8}La_{0.2}Fe_5O_{12}$ (GIG) on a $(GdCa)_3(GaMgZr)_5O_{12}$ (GGG) substrate. By inserting a Mach-Zender interferometer before the Kymera 193i-B2 imaging spectrometer, we further measured the complex refractive index of an X-ray excited material using spectral interferometery [1]. The interferometer is used to spatially overlap the split beam so that the perturbed area interferers with the unperturbed one. From this, one can infer the phase shift induced by the change in the refractive index since the sample surface is imaged onto the imaging spectrometer slit. By using a linearly chirped probe, giving a univocal relation between the instantaneous frequency and time, one can encode the pulse spectrum with the time history of the perturbation. This allows measuring of the time-history of the perturbation in a single laser shot. The measurements were conducted at the Single Particles, Clusters, and Biomolecules and Serial Femtosecond Crystallography (SPB/SFX) instrument [7], at the SASE-1 branch at the European XFEL.

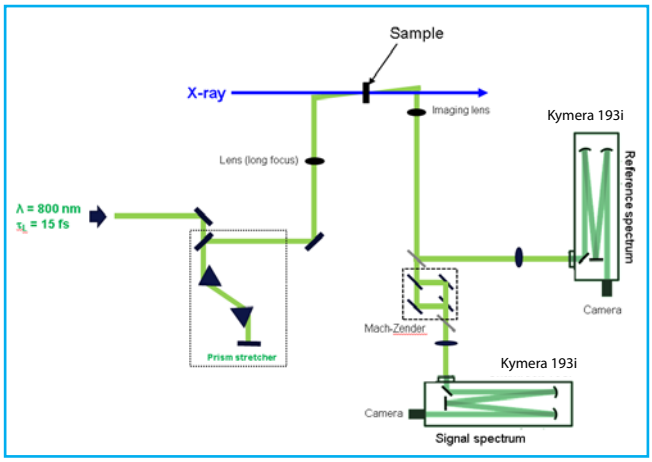

Figure 1 Schematic of the experimental setup.

Results and conclusion
We successfully measured the timing jitter, which at that time was 378 fs RMS [2], using the Kymea 193i imaging spectrograph. This jitter is expected to be improved significantly by implementing a new optical synchronization system to the optical laser.

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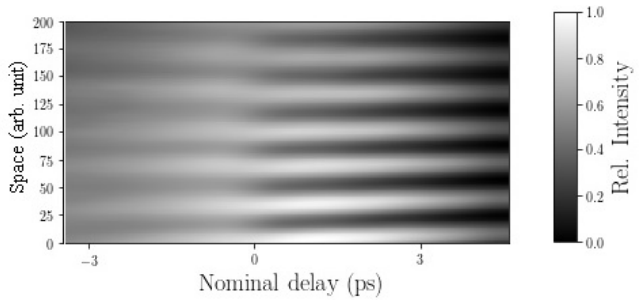

Figure 2 Single shot image obtained with the Kymera 193i-B2 spectrograph. The horizontal axis is the wavelength therefore time (full time window ~ 13 ps). The image shows both change in amplitude and phase (by fringe shift) due to modification of the complex refractive index upon X-ray excitation. The X-ray is arrived at the nominal delay of 0 ps.

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