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Measuring the temporal coherence of a high harmonic generation setup employing a Fourier transform spectrometer for the VUV/XUV

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ABSTRACT

In this experiment we used an 800 nm laser to generate high-order harmonics in a gas cell filled with Argon. Of those photons, a harmonic with 42 eV was selected by using a time-preserving grating monochromator. Employing a modified Mach–Zehnder type Fourier transform spectrometer for the VUV/XUV it was possible to measure the temporal coherence of the selected photons to about 6 fs. We demonstrated that not only could this kind of measurement be performed with a Fourier transform spectrometer, but also with some spatial resolution without modifying the XUV source or the spectrometer.

1. Introduction

The measurement of temporal coherence of visible or infrared radiation can be done employing equipment like a Michelson interferometer [1]. In a Michelson interferometer the beam is split in two components, where one of them is delayed with respect to the other by changing the path length in one of the interferometer arms. Both beams are then recombined and the resulting interference pattern is recorded as a function of path length difference. By scanning the delay and observing the changes of the interference fringes, one can measure the field autocorrelation of the radiation [2]. From that one can get information about the temporal coherence as well as the spectrum of the radiation. Temporal coherence is seen in the presence or absence of interference between the two overlapping beams while spectral information can be retrieved through a Fourier transformation of the recorded interference fringes as function of path length difference [2]. Although the principle is the same for shorter wavelengths in the Vacuum Ultraviolet (VUV) or Extreme Ultraviolet (XUV) regime, the implementation is much more difficult. Key reasons for this are that VUV/XUV radiation is strongly absorbed by all kinds of materials, even air, making it necessary to work in vacuum and to use only reflective optics as well as special radiation detectors. Furthermore, one has to keep the angle of incidence large enough to achieve total external reflection, since reflectivity at normal incidence is very poor at these photon energies [3]. This also implies that the number of reflections should be kept at a minimum. Additionally, the requirements on the surface quality of the optics increase with decreasing wavelength, and so do the demands on mechanical stability and positioning precision of movable parts.

Although the demands on a setup rise with the photon energy, the temporal coherence of XUV pulses has been measured. This was done e.g. for Free Electron Lasers (FELs) pulses with schemes employing wave front dividing beam splitters [4,5] or for collisionally pumped soft-X-ray lasers using multilayer intensity dividing beam splitters [6].

To measure the temporal coherence of XUV radiation produced in a High Harmonic Generation (HHG) process [7], one can use dedicated setups as done in Refs. [8,9]. In these setups the driving laser beam is split prior to the HHG generation in a semitransparent intensity-dividing beam splitter. These two phase-locked beams are then used to generate two separate XUV sources in the same gas very close to each other. Hence, the XUV radiation from both sources is also phase-locked and the coherence properties can be analyzed by overlapping the two XUV beams. However, this method cannot be used easily at existing sources and beamlines due to limitations in laser power and accessibility of the setups.

The development of wave front dividing beam splitting methods made a recent development of Fourier transform spectroscopy

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into the VUV and XUV region possible [10,11]. This allows Fourier transform spectrometers to be used in the VUV and XUV range to analyze the so-called visibility of the interference pattern in the same way as can be done for visible and infrared sources. Thus, the measurement of the temporal coherence of a source, without the need of modifying it is possible.

A Fourier transform spectrometer, although capable of measuring the coherence length, is however not capable of measuring the pulse length. A proper measurement of the pulse length is a topic of its own and is discussed for optical wavelengths in detail e.g. in Ref. [12]. The major difference is that one needs to measure not the field autocorrelation of the signal but the intensity autocorrelation which requires a second order process. Such a second order process requires high light intensity and adds additional complexity which makes the measurement of the pulse length unachievable with a conventional Fourier transform spectrometer.

2. Experimental

In order to demonstrate the capability of using a Fourier transform spectrometer (FTS) to measure the temporal coherence of short XUV pulses, the HELIOS (*High Energy Laser Induced Overtone Source*) HHG light source at Uppsala University [S. Plogmaker et al. (in manuscript)], and an in-house developed Mach–Zehnder type interferometer for the XUV radiation [11] were used. Briefly, HELIOS is an HHG setup which uses an amplified commercial Ti:sapphire based laser system (Coherent Inc.) with a center wavelength of 800 nm and a pulse duration of 35 fs. The repetition rate of the system is 5 kHz resulting in a total output power of 12.5 W. The laser is focused into a gas cell filled with Argon or Neon to generate XUV radiation. The generated radiation is inherently coherent [13] and the upper limit of its pulse duration is set by the pulse duration of the driving laser. The energies that are generated at HELIOS today are in the order of 20–70 eV and, since the radiation is generated in noble gases, the harmonics are limited to the odd harmonics of the energy of the driving laser photons.

Since several harmonics are generated in the HHG process at the same time a monochromator is used to select a single harmonic. A traditional monochromator design would prolong the pulse due to the path length difference introduced by every single grove of the grating. To keep this prolongation small, HELIOS uses a monochromator design employing a grating in a so called off-plane mount [14,15]. The HELIOS light source will be discussed in further detail in a forthcoming publication [S. Plogmaker et al. (in manuscript)].

The spectrometer used in this experiment is a FTS of modified Mach–Zehnder type [11]. It is equipped with a large-aperture comb-like wave-front-dividing beam splitter, made from a super polished single crystal silicon mirror. An identically slotted mirror is used as a beam mixer. The FTS was earlier tested at the I3 beamline [16] at the Max IV laboratory, Lund, Sweden, both in direct [17] and indirect detection of the beam, and has been shown to work at least up to 55 eV photon energy.

In the current experiment, Argon was used in the gas cell and the FTS was mounted directly behind the monochromator allowing measurements of the temporal coherence of a single harmonic of the HHG radiation. A schematic drawing of the setup used in the experiment is shown in Fig. 1. A typical image of the XUV radiation on the detector of the FTS can be seen in Fig. 2. Note that the path length difference in Fig. 2 a) is larger than the temporal coherence and hence no interference pattern can be seen. The fringes visible in Fig. 2 a) are static and do not change when the path length difference between the arms of the spectrometer is varied. This intensity pattern has its origin rather in the light passing first the beam splitter and then the beam mixer which both act as multi slits. The fringe pattern caused by the interference at zero path length difference can be seen in Fig. 2 b). Additionally, in both Fig. 2(a and b), one can see a grid like structure which probably originates from a meshed aluminum foil in the monochromator that is used to block the infrared driving laser while transmitting the XUV radiation.

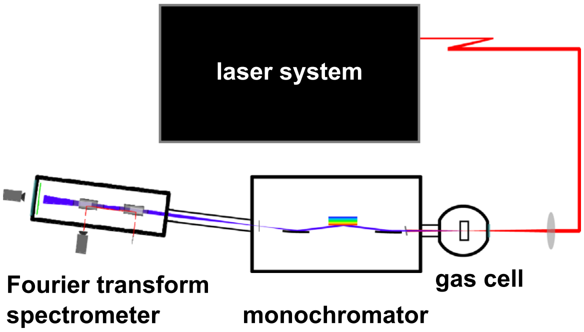

Fig. 1. Schematic drawing of the HELIOS source with the Fourier transform spectrometer attached behind the monochromator.

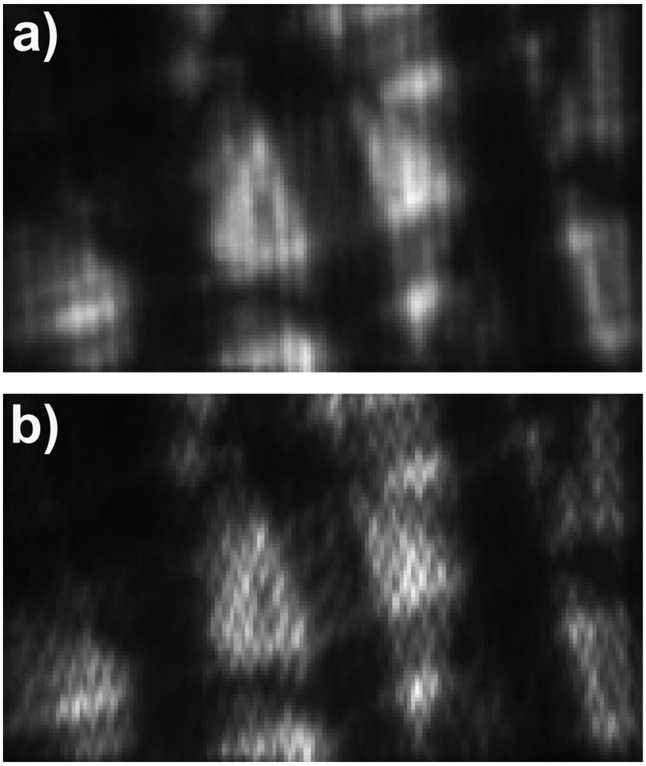

Fig. 2. FTS detector image of the 27th harmonic. The path length difference is 1.35 μm (corresponding to 45.1 fs) for a) while it is 0 μm for b). Hence, interference fringes are visible in b) but not in a). See text for details about the interference pattern.

3. Results

The temporal coherence can be determined by measuring the visibility of the interference fringes when changing the delay between the two beam paths in the spectrometer. The visibility V_b is defined as [18]

$$V_b = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} \tag{1}$$

where I_{max} and I_{min} are the intensities of constructive and destructive interference of the observed fringes. The temporal