Spectrally resolved wavefront characterization of broadband ultrafast high-harmonic pulses

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Abstract. We demonstrate a sensor that measures wavefronts of multiple extreme ultraviolet wavelengths simultaneously. By incorporating transmission gratings into the apertures of a Hartmann mask, we can record wavefront information for series of discrete harmonics from a high-harmonic generation source in a single camera exposure, without the need for scanning parts. Wavefronts of up to nine high harmonics at 25-49 nm wavelength are retrieved, and ultrafast spatiotemporal couplings can be detected.

1. Wavefront sensing of ultrafast extreme ultraviolet sources

High-harmonic generation sources have become well-known as table-top sources of coherent extreme ultraviolet (EUV) pulses, and are used in many applications such as high-resolution imaging, time-resolved soft-X-ray spectroscopy and attosecond physics. In many of these applications, accurate knowledge of the EUV wavefront is important to correctly interpret the results. While many wavefront measurement methods have been developed for visible as well as EUV spectral ranges, most of them lack spectral selectivity, and are therefore limited in their ability to properly characterize wavefronts of intrinsically broadband ultrafast sources.

High-harmonic generation (HHG) produces an intrinsically broad EUV and soft-X-ray spectrum, typically consisting of a number of discrete harmonics. Different methods have been developed to record spectrally-resolved HHG wavefronts [1-3], but these all rely on mechanical scanning to obtain a complete dataset. As HHG is a highly nonlinear process, a single-shot measurement method would be highly desirable to accurately characterize wavefronts of ultrafast HHG pulses in the presence of significant shot-to-shot variations. Here we present a new type of EUV wavefront sensor, which enables single-shot measurements of spectrally-resolved wavefronts for a wide range of harmonics.

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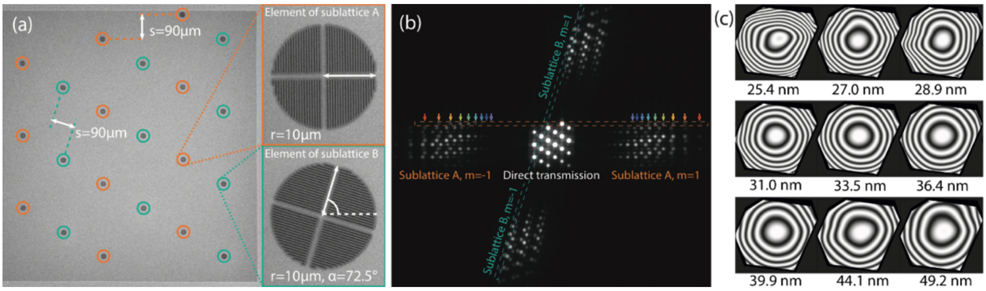

Fig. 1. (a) SEM image of the spectroscopic Hartmann mask. The apertures of a conventional Hartmann sensor are replaced by small transmission gratings, allowing both spectrum and local wavefront tilt to be measured at each aperture. The apertures are positioned such that spectra of neighboring apertures do not overlap. Furthermore, the apertures can be divided in two subsets with different grating direction, enabling a higher density of apertures for wavefront sampling. **(b)** Typical spectroscopic Hartmann wavefront measurement. The labels and color coding correspond to features in (a). The arrows indicate positions of the spots of different harmonics corresponding to one SHM aperture. **(c)** Wavefronts retrieved from the measurement in (c), visually represented as interfering with a plane wave (2π phase shift between adjacent bright fringes).

2. Spectrally resolved EUV wavefront measurements

In a conventional Hartmann-type EUV wavefront sensor, the transmission of an array of apertures is measured. A comparison of the measured spot pattern and the mask geometry allows for the retrieval of wavefront tilts at all the illuminated apertures. The wavefront can then be reconstructed by integration. To add spectral resolution to such a measurement, we replace the individual apertures of the Hartmann mask by small transmission gratings. These gratings then produce replicas of the original Hartmann pattern in the ±1st diffraction orders. For a sufficient grating pitch and camera distance, it is possible to resolve Hartmann spot patterns for the individual harmonics in the illumination.

We fabricated such a spectroscopic Hartmann mask (SHM) by focused ion-beam milling in a 1x1mm gold-coated silicon nitride film. In order to achieve a higher density of apertures without causing significant overlap between spots from different harmonics and adjacent apertures, we use two subsets of apertures with a different grating direction (Fig. 1a). A typical wavefront measurement of HHG produced in Argon with 800 nm driving wavelength can be seen in Fig. 1b. The image can be divided into five parts, each containing a group of spots. In the center, the direct transmission of the apertures results in the spot pattern that would be measured using a traditional Hartmann mask. The four groups of spots around the central pattern correspond to the ±1st orders of diffraction of the gratings with the horizontal and (near-)vertical orientation. In these diffracted patterns the spots of the individual harmonics are all well separated, enabling a wavefront reconstruction for all harmonics simultaneously from this single image [4].

Local wavefront tilts are obtained by finding the center of mass of the ±1st diffraction orders for each spot and comparing the position with the known reference pattern of the mask itself. Wavefront reconstruction then proceeds in a similar way as normal Hartmann mask analysis, with some minor modifications to accurately incorporate geometrical effects of the grating diffraction. From the data of Fig. 1b, we reconstruct wavefronts of nine harmonics in the wavelength range of 25 to 49 nm (Fig. 1c). We find near diffraction-limited wavefronts for the brightest high-harmonics, while the weaker harmonics show increased aberrations due to less optimal phase matching conditions.

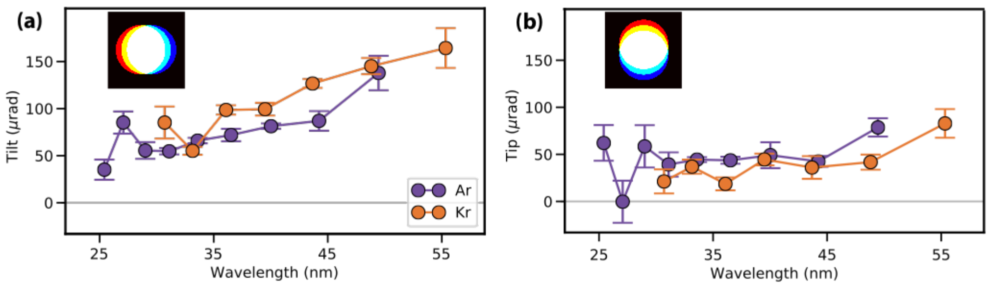

Fig. 2. Measured relative wavefront tilt in the horizontal (tilt, (a)) and vertical (tip, (b)) directions. A wavelength-dependent tilt is observed in the horizontal plane, which corresponds to a small spatial chirp (pulse front tilt) on the HHG pulses.

3. Detecting pulse front tilts in ultrafast EUV pulses

A remarkable feature of the SHM is the ability to measure relative wavefront tilts between the individual harmonics. Knowledge of a possible relative tilt between different harmonics is relevant for many ultrafast experiments, as it constitutes a spatial chirp, which is equivalent to a tilt of the pulse front. Such a spatial chirp can modify the outcome of experiments that are sensitive to space-time coupling of ultrashort pulses. Introduction of a controlled pulse front tilt is also at the basis of the attosecond lighthouse effect [5].

A wavefront tilt appears as a constant shift for all spots of a given wavelength with respect to the reference grid, so a pulse front tilt would be visible as a wavelength-dependent variation in wavefront tilt. Because in a SHM measurement the wavefronts of all harmonics are measured simultaneously in a common geometry, the relative difference in tip and tilt for different harmonics can readily be measured [4]. Measurements of the relative wavefront tilt observed for HHG in Argon and Krypton are shown in Fig. 2. A linear variation in tilt as a function of wavelength is clearly visible, revealing the presence of a small pulse front tilt on the HHG beam. The observed tilt is the same for both gases, indicating that it is caused by the presence of a small pulse front tilt on the incident driving beam. This ability of the SHM to quickly quantify such small tilts enables alignment and optimization of broadband HHG wavefronts and spatiotemporal couplings, and can be important in the characterization of HHG sources for advanced ultrafast experiments. For sufficiently bright sources, even the wavefront of single HHG pulses can be fully characterized.

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