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Optics-Free Focusing and Application to Spectral Filtering of XUV Beam

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Abstract: We experimentally characterize XUV intensity profiles and wavefronts, and demonstrate XUV beams focusing without resorting any optics. We use this coherent effect to spectrally filter group of harmonics. Simulations show possible control of attosecond temporal structure.

1. Introduction

Ultrafast phenomena studies rely mainly on pump-probe experiments [1]. XUV beam produced by high-order Harmonic Generation (HHG) are commonly used as a table-top source of attosecond pulses, allowing high temporal resolution. In order to perform XUV-pump-XUV-probe experiments and non-linear optics in the XUV range [2], the generation of intense XUV radiations becomes indispensable but remains a challenge. This can be done by increasing the energy, shortening the duration of the XUV pulse, or by controlling the focusing properties of the XUV beam which strongly depend on the harmonic order. Recently, we have demonstrated the possibility of generating harmonics as either diverging or converging beams showing the ability to control the XUV beam spatial properties [3,4]. This so-called optics-free focusing results from the control of the XUV wavefront in the generating process. We propose to use this technique to control the spatio-temporal properties of the XUV beam.

First, spatial characteristics measurements of XUV beams by the technique of the spectrally resolved wavefront characterization of the XUV radiation are presented. This constitutes the direct measurement of coherent focusing. Second, as a consequence of coherent focusing, spectral filtering of harmonics without using any optics is demonstrated. Then we describe the theoretical model used to compare with experimental results. This model will allow the determination of the temporal structures of the XUV pulse.

2. Spatial characteristics measurements of XUV beam

The experimental setup has been described in details in [3]. We used 9mJ of laser energy of the Terawatt Ti:sapphire laser system delivering 800-nm, 100-mJ, 40-fs pulses at a 10-Hz repetition rate. The infrared (IR) beam spatial quality is ensured by spatial filtering and wavefront optimization by a deformable mirror (ISP System), coupled to a wavefront sensor (Imagine Optic). The beam is then focused by a 2-m focal length spherical mirror leading to an 85 μm focused laser beam waist (peak intensity of $4 \cdot 10^{14} \text{ Wcm}^{-2}$ at focus) in a gas jet of neon. The gas jet can be moved longitudinally over 15 cm around IR focus. Generated high-order harmonics are analyzed by an XUV spectrometer and the spatially resolved spectra are analyzed 2.9 m after the laser focus. A movable 140- μm -diameter pinhole can be inserted 37 cm after the IR focal plane to characterize the intensity profile and wavefront of each harmonic.

Characterization of radii of curvature for each dispersed harmonic beam has been performed using the SWORD (Spectral Wavefront Optical Reconstruction by Diffraction) technique [5]. The measurement principle has been described in [4]. Fig. 1 presents the results of the SWORD measurement for harmonics H31, H39 and H47. Fitting the measured XUV intensity profiles (a) and reconstructed spatial phases (b) by Gaussian and quadratic functions, respectively, provides the beam size w_q and the radius of curvature R_q of each harmonic at the pinhole plane. We find that the beam sizes and wavefront curvatures change with the harmonic order and gas jet position. We observe that the spatial profile is close to Gaussian profile and that the phase is quadratic. Under these conditions, we can infer that the XUV beam propagates like a Gaussian beam and retrieve both the size $w_{q,0}$ and the position $z_{q,0}$ of the waist of the considered harmonic order q , for each position of the gas jet. As pointed out in Veyrinas *et al.* [4],

harmonic waist sizes and positions can be very different for different harmonic orders, depending on the gas jet positions. More precisely, we have determined that for a gas jet far before the IR focus ($z_{\text{jet}} = -40$ mm), the waists are real and are positioned well after the IR focus, demonstrating convergent beams focused in a few micrometer size spots. On the contrary, XUV beams are divergent for z_{jet} near the IR focus and waists can be virtual [4]. These measurements are in good qualitative agreement with the simulated results reported by Quintard *et al.* [3] where harmonic optics-free focusing was demonstrated by means of the of the XUV beam spatial chirp induced by the spatial chirp of the IR.

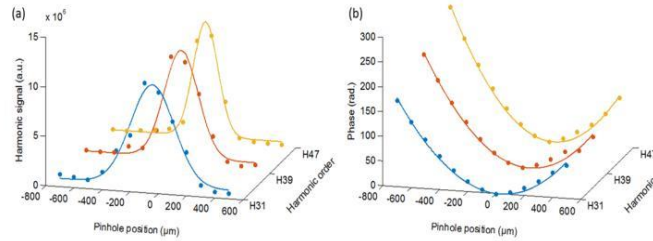


Fig. 1. Measured intensity profile (dots) and Gaussian fit (line) (a) and reconstructed spatial phase (dots) and quadratic fit (line) (b) of harmonics H31 (blue), H39 (orange) and H47 (yellow), for $z_{\text{jet}} = -35$ mm. We obtain $w_q = 309, 240,$ and $174 \mu\text{m}$ and $R_q = 363, 396,$ and 382 mm for harmonics H31, H39 and H47, respectively.

3. Spectral filtering without any XUV optics

We demonstrate a direct application of the XUV beam properties controlled by performing XUV spectral filtering without using any XUV optics. This is realized by comparing the spatially-resolved HHG spectrum obtained with the pinhole centered on the pathway of the harmonic beam and the spectrum obtained without the pinhole. The transmittance (T) is then defined as the ratio of the HHG spectra after integrating over the vertical coordinate with and without pinhole. Assuming the generation in a thin medium (when the length of the generation medium is smaller than Rayleigh range of the fundamental laser beam), phase-matching effect can be treated separately. The spatial distribution of the XUV beam in far field is expressed by a Fraunhofer integral where the source term is obtained by solving the Time-Dependent Schrödinger Equation (TDSE) [6]. From this model, we determine the size of each harmonic beam on the pinhole and then calculate the transmittance through it as realized experimentally.

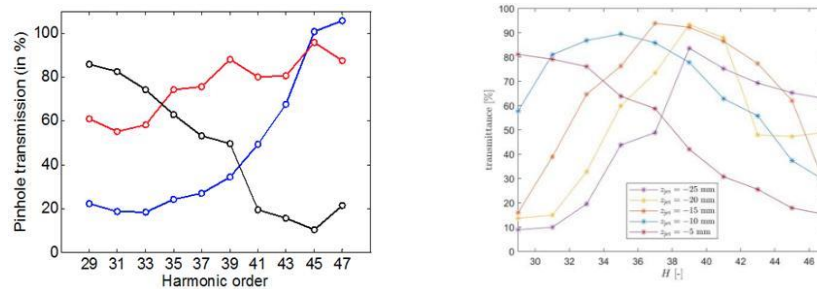


Fig. 2. Left panel: Measured transmittance of harmonics H29 to H47 for $z_{\text{jet}} = -58, -36,$ and -20 mm (black). Right panel: Transmittance versus harmonic order for five gas jet positions computed with 1D-TDSE model.

Left panel in Fig. 2 displays the measured transmittance of harmonics H29 to H47 for $z_{\text{jet}} = -58, -36,$ and -20 mm and clearly shows that the characteristics of this filter are fully tunable by adjusting the gas jet position with respect to the IR focus. Low-pass (black curve), high-pass (blue curve) and broadband (red curve) filters are obtained. In all cases, the high spectral selectivity and contrast ensure a proper selection of a group of harmonics. This can be compared to simulation results shown in right panel in Fig. 2 where transmittance as a function of harmonic order for $z_{\text{jet}} = -5, -10, -15, -20,$ and -25 mm is plotted. For large negative values of z_{jet} , the transmittance increases

with harmonic order as for z_{jet} nearer to IR focus, the transmittance decreases with harmonic order. For intermediate jet positions, the transmittance presents a bell like shape ranging from 20% to 100%. These curves can be compared with experimental data, showing an overall agreement. Finally, this spectral filtering is accompanied with a strong rejection of the IR fundamental beam ($T < 1\%$) avoiding the use of metallic filters that usually reduce significantly the XUV signal. We point out here that the present approach does not require the use of any XUV optics and thus does not suffer from limitations inherent to this energy range and encountered with traditional optical technique.

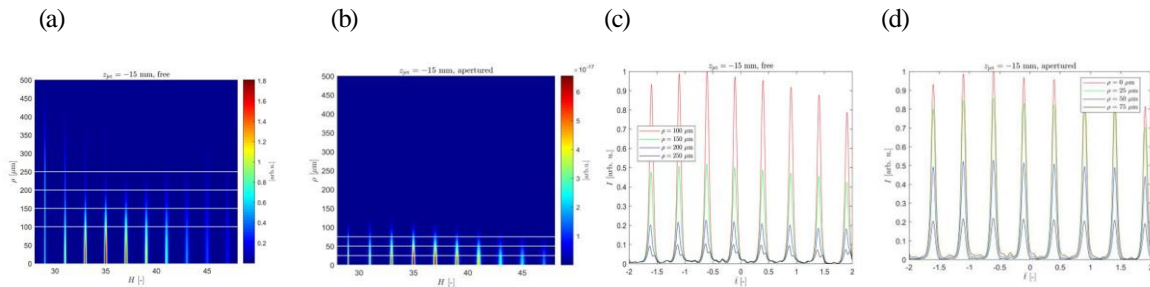


Fig. 3. Spatially resolved spectra for free propagation (a) and with filtering (b) at 1m from IR focus. White lines correspond to radii at which temporal structures are depicted in (c) for free propagation and (d) with filtering.

We further simulate the spatially resolved spectra and the temporal structure of attosecond pulses for the experimental conditions. On Fig. 3, the spatially resolved spectra for the case of gas jet position = -15 mm before IR focus with (b) and without (a) filtering are presented. The temporal profile of the XUV beam for different values of radii ρ in the case of free propagation (c) and with filtering (d) are also plotted. The first observation is the effective size reduction of the waist of harmonics. The waist of harmonics also presents much less fluctuations from one harmonic to the next. The radius ρ spans an intensity range which covers the full spatial evolution of the XUV beams. In Fig. 3d, we observe a much more regular evolution of the temporal profile with radius ρ as compared to the unfiltered case of Fig. 3c. In particular, for $\rho = 250 \mu\text{m}$, a double hump appears in the temporal profiles in Fig. 3c due to the contribution of long trajectories which are not filtered in that case. We have demonstrated the same features for other gas jet positions, the main difference being essentially quantitative.

4. Conclusion

We have experimentally demonstrated spatial properties control of XUV harmonic beams as a function of generating medium positions relative to IR focus, and observed that optics-free focusing of high-order harmonics can be obtained in specific conditions. We have also demonstrated experimentally and theoretically adjustable XUV spectral filtering with high contrast without any resorting XUV optics. We have developed a model that shows that spatio-temporal structure homogeneity will also benefit from the filtering, leading to better control of the spatio-temporal structure of attosecond pulses.

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