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## Near diffraction limited coherent diffractive imaging with tabletop soft x-ray sources

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**Abstract.** Tabletop coherent x-ray sources hold great promise for practical nanoscale imaging, in particular when coupled with diffractive imaging techniques. In initial work, we demonstrated lensless diffraction imaging using a tabletop high harmonic generation (HHG) source at 29 nm, achieving resolutions  $\sim 200$  nm. In recent work, we significantly enhanced our diffractive imaging resolution by implementing a new high numerical aperture (up to  $NA=0.6$ ) scheme and field curvature correction where we achieved sub-100 nm resolution. Here we report the first demonstration of Fourier transform holography (FTH) with a tabletop SXR source, to acquire images with a resolution  $\approx 90$  nm. The resolution can be refined by applying phase retrieval. Additionally, we show initial results from FTH with 13.5 nm HHG radiation and demonstrate  $\sim 180$  nm resolution.

### 1. Introduction

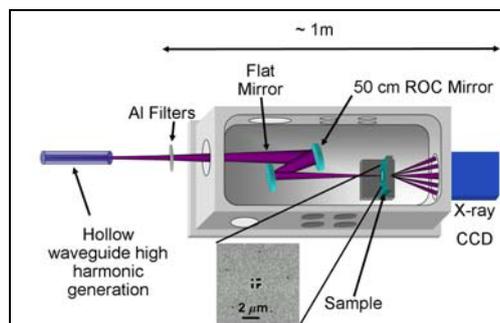
Lensless imaging, also known as x-ray diffractive microscopy, is a relatively new technique that is particularly suited to x-ray imaging, enabling high-resolution imaging of non-crystalline, aperiodic samples such as biological materials [1]. This technique provides a large depth of field, insensitivity to alignment, and near-wavelength-limited resolution without the need for complex optical systems. In past work, we demonstrated lensless diffraction imaging using a tabletop high harmonic (HHG) soft x-ray source at 29 nm, achieving resolutions  $\sim 200$  nm [2]. By implementing a high numerical aperture (up to  $NA=0.6$ ) scheme and curvature correction, we achieved resolutions  $< 100$  nm using two approaches. First, we use phase retrieval with the GHIO algorithm to achieve a resolution of 94 nm with a 29 nm HHG source, and a resolution of 71 nm using a 47 nm capillary discharge laser [3].

In this work, we report the first demonstration of Fourier transform holography with a tabletop soft x-ray source, acquiring images with a resolution  $\approx 90$  nm. Fourier transform holography (FTH) is a diffractive imaging technique that is complementary to coherent diffractive imaging

(or lensless imaging). Instead of using an iterative phase retrieval algorithm to extract the phase from the measured data, FT holography uses a reference beam that interferes in the far field with the light scattered off of the sample in a hologram. The magnitude of the Fourier transform of the hologram produces the spatial autocorrelation of the sample. For this paper, we used a geometry which produces a reference beam by introducing multiple holes surrounding the sample [4]. In the spatial autocorrelation, each reference hole produces an image of the sample and its complex conjugate. These individual ‘sub-images’ can be added up to increase the signal to noise ratio of the image [5]. Thus, this technique was chosen as a way to increase the signal to noise of images taken with the high harmonic source that will have decreasing flux at higher photon energies, however, for the photon energies demonstrated here, adding the sub-images was not necessary.

## 2. Experiment

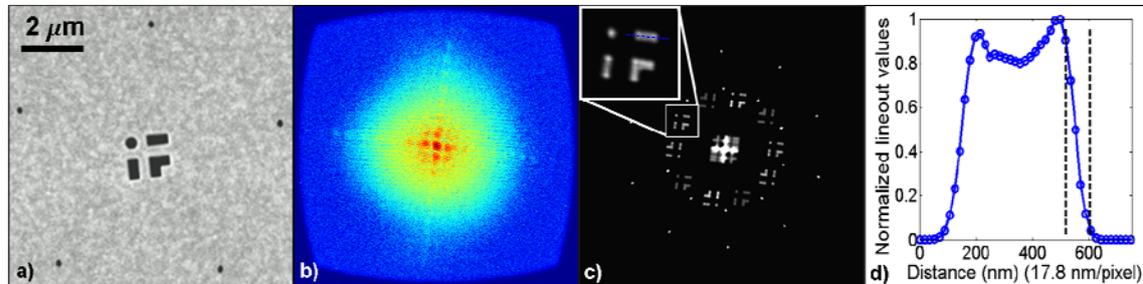
Figure 1 shows the experimental setup for Fourier Transform Holography with a tabletop soft x-ray source. High harmonic generation occurs when 25 fs pulses from a 4 W Titanium-sapphire laser operating at 3 kHz are focused into a hollow-core capillary gas filled waveguide. The waveguide was filled with 70 Torr of Ar for 29 nm and 400 Torr of He for 13.5 nm generation. Two 200 nm thick filters (Al for 29 nm and Zr for 13.5 nm) remove the near-IR light while transmitting the soft x-ray harmonics. Two Mo-Si multilayer mirrors select either 27<sup>th</sup> harmonic at 29 nm or the 57<sup>th</sup> harmonic at 13.5 nm and gently focus it onto a sample a few centimeters from a CCD which records the hologram.



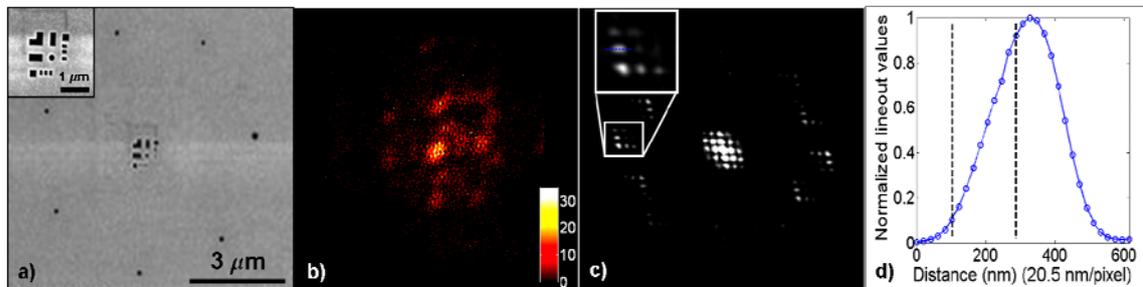
**Figure 1.** Compact lensless diffractive microscope used with both a 29 nm HHG source and a 13.5 nm HHG source.

*2.1. FT holography with 29 nm illumination.* Figure 2 shows the results with the 29 nm source. A FT holography sample was used with five reference holes each with an approximate diameter of 130 nm. These samples were constructed by milling out holes in 300 nm of gold on a 100 nm thick Si<sub>3</sub>N<sub>4</sub> window with a focused ion beam. Figure 2 shows an SEM image of the sample, the collected diffraction pattern from 10 minutes of exposure, the autocorrelation reconstruction, and a lineout showing the reference hole limited resolution of 89 nm. However, with longer exposure times, scattered light can be collected to higher angles that will support higher resolution image. This information can then be extracted using an iterative phase retrieval algorithm [4]. With an exposure time of 80 minutes and refining the image with phase retrieval, we demonstrate a resolution of 53 nm with 29 nm illumination [6].

*2.2. Initial FT holography images with 13.5 nm illumination.* We also present initial images using high harmonic light at the technologically important 13.5 nm wavelength. A Fourier-transform holography sample was used with seven reference holes each with an approximate diameter of 200 nm. Figure 3 shows an SEM image of the sample, the collected diffraction pattern from 40 minutes of exposure, the autocorrelation reconstruction, and a lineout showing the theoretically-limited resolution of ~150 nm based on the reference hole diameter.



**Figure 2.** (a) SEM image of sample with five reference holes (b) 29 nm hologram from 10 minutes of exposure after curvature correction (log scale) (c) autocorrelation reconstruction of the sample (d) line cut through one sub-image showing 90 nm resolution.



**Figure 3.** a) SEM image of FTH sample with seven reference holes b) 13.5 nm hologram from 40 minute exposure (log scale) c) autocorrelation reconstruction of the sample d) line cut through one sub-image showing 184 nm resolution.

### 3. Conclusion

As higher brightness, shorter wavelength, tabletop sources become available, this high numerical aperture scheme – a first for diffractive imaging with x-rays – will make possible near-wavelength resolution below 10 nm. Important applications of this work exist in nanotechnology, lithography, materials science, and biological imaging. Moreover, the ultrafast (fs) duration of the HHG pulses will enable imaging of dynamic systems with high temporal resolution.

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