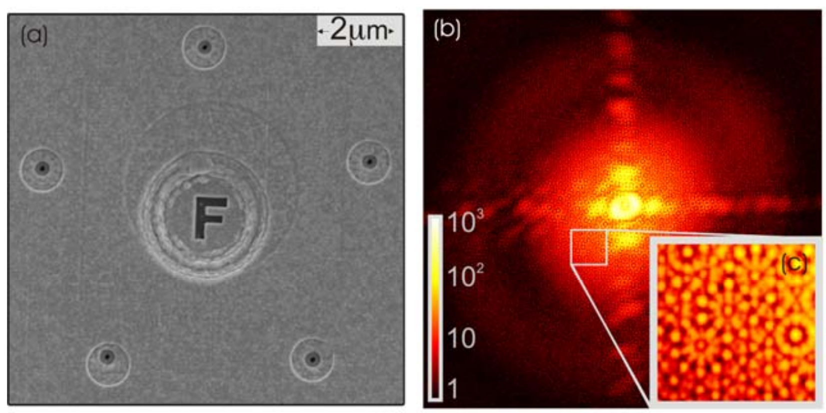
Multiple Reference Fourier Transform Holography: Five Images for the Price of One

Improving the quality of a high magnification image on an optical microscope is simply a matter of cranking up the intensity of the illumination lamp. The same is true for x-ray microscopes, but complications arise when there just aren't enough x-rays or even worse when the sample is susceptible to damage caused by the intense x-ray beam. To address these challenges we have demonstrated a novel technique for improving the quality of a microscopic image without increasing the x-ray exposure to the specimen. This affords new opportunities to explore materials prone to soft x-ray damage, like polymer or biological samples. Our technique uses coherent x-ray scattering to simultaneously acquire multiple images of a specimen, which can easily be combined later to enhance the image quality. Applying our technique in the weak illumination limit we imaged a nanoscale test object by detecting only 2500 photons.

This holographic technique can even improve image quality under stroboscopic illumination by an ultrafast pulsed x-ray source. Such x-ray pulses can probe sub-picosecond dynamic processes at nanometer length scales, and will be generated by x-ray Free Electron Lasers like the Linac Coherent Light Source (LCLS) at SLAC.



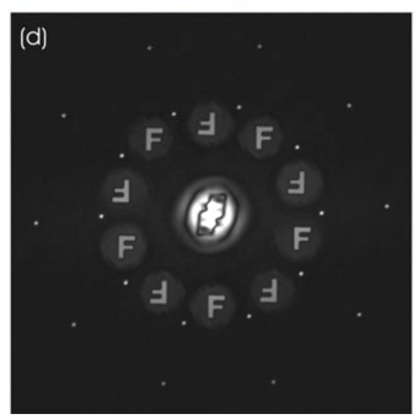
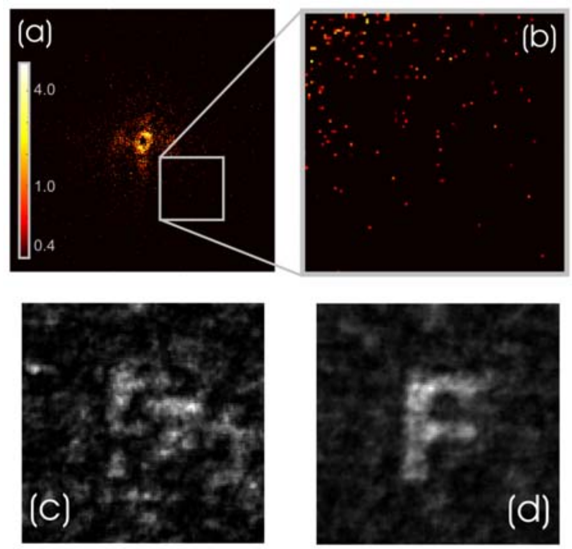


Figure 1. (a) SEM image of the holographic Au mask featuring identical reference holes surrounding the sample--a block letter F. (b) The detected hologram is shown in false color with the number of photons detected denoted by the scale bar. (c) An enlargement of the five-fold symmetric interference pattern resulting from references. (d) Autocorrelation resulting from the Fourier reconstruction of the hologram.

Bright bursts of x-rays from the LCLS will not arrive until 2009. Hence, we carried out our proof-of-principle experiment at SSRL beamline 5-2, a newly commissioned undulator beamline optimized for soft x-ray coherent scattering. One feature of coherent scattering is the ability to reconstruct a sample's microscopic image from the scattering pattern alone, without using any lenses. This can be achieved with a simple form of holography, known as Fourier Transform Holography (FTH). (Eisebitt, *et. al.*, *Nature*, **432**, pp 885-887, 2004) In FTH, coherent light scattered by a sample interferes with light scattered from a known reference aperture to form a hologram. An image of the sample can be recovered analytically by Fourier transformation of the hologram at a spatial resolution comparable to the size of the reference aperture.

In our example, the holographic references are defined by five nanoscale holes that penetrate a soft x-ray opaque film as shown in Fig. 1 (a). The test sample is a block letter F, which is little over 1 μm tall. The coherent diffraction pattern shown in Fig. 1 (b) was recorded as a hologram with soft x-ray (λ=1.58 nm) illumination of the holographic mask. Ten reconstructed images of the sample appear in Fig. 1 (d) calculated by Fourier transformation of the hologram, but only five out of the ten images are unique. The key element to this experiment is the implementation of multiple holographic references. Each reference simultaneously provides a copy of the image in the reconstruction without increasing the exposure to the sample. These images are clear representations of the sample because the hologram contains ~$7x10^6$ detected photons. In the weak illumination limit, photon noise degrades the clarity as explained in Fig. 2.

Figure 2: To mimic the finite number of photons in an x-ray pulse we recorded a hologram with significantly reduced photon flux (2500 detected photons in Fig. 2a *vs.* $7x10^6$ photons in Fig. 1b). The isolated dots in Fig. 2b are single photon detection events. A single reconstructed image of the letter F is barley visible in Fig. 2c, but after carefully aligning and averaging it with the four other images, the F is clearly visible in Fig. 2d. The improvement in image quality scales with the square root of the number of images averaged.



Coherence, intensity and pulse structure are the hallmarks of the next generation of x-ray light sources. With a hunger for coherence and compatibility with pulsed illumination, lensless imaging is well suited for these sources.

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