Lensless Imaging of Magnetic Nanostructures by X-ray Spectro-Holography

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The unprecedented properties of X-ray free electron lasers (X-FELs) under development world wide will open the door for entirely new classes of experiments. The ultra-short time structure of the ultra-bright x-ray pulses will revolutionize the field of femtosecond x-ray science, since it will become possible to obtain sufficient information about a system from probing it with a single x-ray pulse. This will for the first time allow investigating the non-repeatable aspects of femtosecond dynamics and thus yield information beyond a statistical description of the occurring processes.

Snap shot imaging of transient states has been a dream that has become much closer to reality with the advent of X-FELs. A particularly powerful and practical technique is lensless imaging on the nanometer length scale with a coherent x-ray beam. This technique has now been demonstrated in practice by Stefan Eisebitt (BESSY) and Jan Lüning (SSRL) and their co-workers. Their implementation of the technique is an extension of lensless Fourier transform holography to the x-ray regime, which detects the far field diffraction pattern of a coherently illuminated object. From such a holographic x-ray diffraction pattern the real space image can be retrieved by a single two-dimensional Fourier transformation. The well-known "phase problem of x-ray scattering" which is the intrinsic loss of the scattering phases in the recorded intensities is overcome by interfering the beam from the sample with a reference beam through a tiny pinhole. This encodes the scattering phases in additional intensity modulations. Since no lenses are involved in the imaging process, the achievable

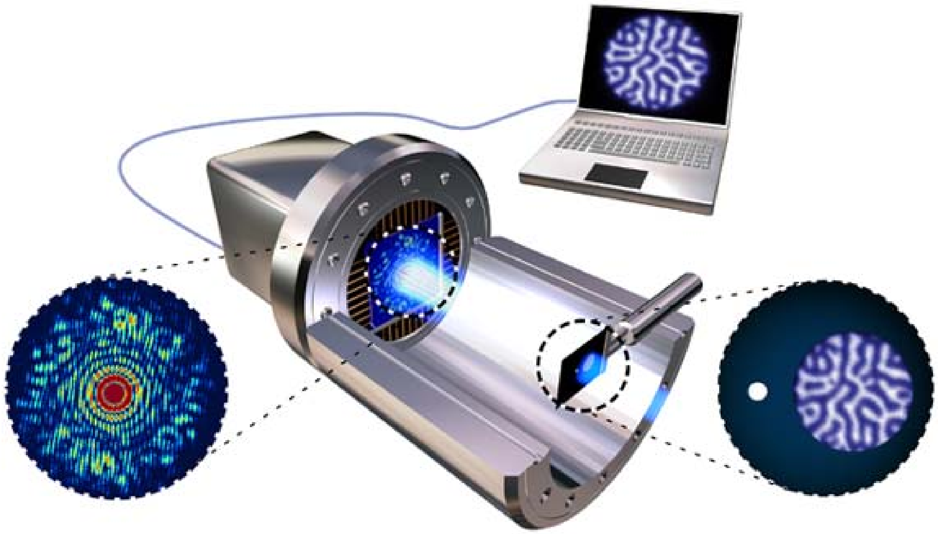

Figure 1: Monochromatic, circularly polarized X-rays are spatially filtered to obtain a coherent x-ray beam, which illuminates a mask–sample structure. Two apertures in this mask define the object and reference beam, and the resulting hologram is recorded on a CCD detector. A single two-dimensional Fourier transformation yields an image of the object. (Image rendered by Michael Hyde, SLAC)

spatial resolution is only limited by the x-ray wavelength. This makes the technique ideally suited for imaging on the nanometer length scale. In addition, the technique is simple and transferable to a wide variety of specimens. By exploiting resonance phenomena in the scattering cross sections, variations in elemental and chemical composition can be imaged. Furthermore, control over the x-ray polarization allows imaging of charge and spin ordering phenomena occurring on the nanometer length scale.

The key aspects of this lensless imaging technique are illustrated in Figure 1. The Fourier transform holography geometry is defined by an x-ray opaque mask with a micrometer-sized object aperture and a nanometer-sized hole that defines the reference beam. The sample, a thin magnetic Co/Pt film with randomly oriented magnetic domain structure, is illuminated through the object aperture. Instead of using an integrated design as shown in Fig. 1 the method can be extended by placing various samples like nanoparticles, colloids or cells into the object area. The shown image of the magnetic domain structure plotted within the object aperture in Figure 1 was obtained by scanning transmission x-ray microscopy. Sensitivity to the magnetization of the domains originates from the x-ray magnetic circular dichroism of the Co L_3 absorption edge. This absorption dichroism goes along with a dichroism in the scattering amplitude, which was used in our lensless method. Transverse coherence is obtained downstream of the monochromator by placing a pinhole aperture in the beam. The Airy disk from the beam transmitted through the pinhole coherently illuminates the object and reference aperture on the mask-sample structure. The intensities of the holographic interference pattern, which is reproduced in Figure 1 as a false color image was recorded with an in-vacuum charge-coupled device (CCD) camera.

Three aspects can be clearly distinguished in this hologram: First, the central intensity disk and the surrounding rings are the Fraunhofer diffraction pattern of the round object aperture. Second, the intensity patches surrounding the central part of the Fraunhofer pattern originate from scattering at the magnetic domains within the object aperture. The random orientation of the worm-like magnetic domains and the presence of a dominant, characteristic length scale, the width of the domains, is reflected by the ring-like arrangement of these intensity patches. Third, the interference between sample and reference beam breaks up the scattering intensities into individual speckles by superimposing a high-frequency oscillation that causes a stripe-like appearance of the scattering pattern.

The object image, retrieved by a single two-dimensional Fourier transformation of the recorded intensities of the Fourier transform hologram, is reproduced on the laptop screen in figure 1. The consistency of the two images of the same magnetic domain structure verifies the true imaging nature of this lensless scattering technique. A spatial resolution of about 50 nm is indicated by the width over which the contrast between black and white domains changes from 10% to 90%. In Fourier transform holography the spatial resolution is defined by the effective source size of the reference beam. Therefore, by narrowing the reference aperture a higher spatial resolution can be achieved. Apart from technical difficulties in the preparation of small, high-aspect apertures, this approach is also limited by the necessity of detectable interference between the reference and object beam. It is therefore interesting to note that two additional ways exist for increasing the spatial resolution. First, if the shape of the aperture defining the reference beam is known to a certain degree, then it is possible to improve the spatial resolution in the holographic image by mathematical deconvolution algorithms. Second, iterative phase retrieval algorithms can be applied to the holographic diffraction pattern to enhance the resolution to match the largest detected momentum transfer.

The experimental simplicity is a clear strength of this lensless imaging technique. It is robust against temperature drifts and vibrations, and virtually no alignment or focusing is required. This makes the technique ideally suited for single shot imaging with a free electron X-FEL

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