Fourier-Transform Holography With Coherent Hard X-Rays

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Abstract. Experimental results of recording Fourier-transform holograms using 14keV synchrotron radiation are presented. A Fresnel zone plate was used as a beam splitter to realize a submicron reference point source by its first diffraction order and at the same time a object wave by the transmitted zero order beam. The holograms were recorded by a high resolution CCD-camera and were numerically reconstructed afterwards.

INTRODUCTION

Experiments with Fourier transform holography (FTH) have already been already successfully done using visible light [1,2] and soft X-rays [3,4,5]. The aim of the presented experiments was to show the possibility of microscopic holography with multi-keV X-rays. We describe experiments with FTH at the ESRF undulator beamline ID18. The main advantage of the FTH technique compared to other microscopic technique is the large fringe spacing in the hologram and therefore low requirements to the lateral resolution of the detector. The resolution of the method is determined by the size of the reference wave and the aperture of the hologram. For the experiment the good coherence properties of the undulator radiation are very useful.

THEORY

In FTH a reference source is placed in the plane of the object. The phase of the wave diffracted by the object can be reconstructed from its interference with the reference wave. The reference point source is formed by the first order diffracted beam of a Fresnel zone plate which is used as a beamsplitter and at the same time the object wave is delivered by the transmitted zero order beam. The resulting interference pattern consists of low constant modulations, in analogy to the double slit experiment. The fringe distance $D_f$ is given by $D_f=\lambda x/s$, where $\lambda$ is the wavelength, $x$ the object to hologram distance and $s$ the reference-to-object distance. If the object is placed close to the reference point and the hologram is recorded in the far field, the intensity distribution in the hologram plane corresponds to the Fourier transform of the transmission function of the object. Therefore the object can be reconstructed by the inverse Fourier transform of the hologram. In order to observe interference effects some requirements on the coherence of the incident wave are necessary. The largest possible object-to-reference distance depends
on the maximum path difference between the object wave and the reference wave up to what they can interfere. This distance is the longitudinal coherence length \( l_l = \frac{\lambda^2}{\Delta \lambda} \) determined by the monochromaticity \( \Delta \lambda / \lambda \) of the beam. For the experimental conditions of \( \lambda = 0.86 \, \text{Å} \) and a Si 111 double crystal monochromator with \( \Delta \lambda / \lambda = 10^{-4} \) we get a value of \( l_l = 0.6 \, \mu m \). From the object distance \( x \) follows the largest possible object to reference distance \( s_{max} = l_l x \). In the experimental set-up this value was \( s_{max} = 1.3 \, mm \).

In order to coherently illuminate the object the incident wave must have a constant phase. The maximum distance in the object plane over which the phase difference of the beam is smaller than one wavelength is described by the transverse coherence length \( l_t = \frac{D \lambda}{d_s} \). It is given by the undulator source size \( d_s \) and the source distance \( D \). From the source size of the undulator beam of 54 \( \mu m \) vertical and 812 \( \mu m \) horizontal and a source distance of \( D = 56 \, m \) follows the transversal coherence length of \( 88 \times 6 \, \mu m^2 \) (vert. \times hor.). For enhancement of the horizontal coherence properties the horizontal beam size was decreased by a slit at 23m upstream of the sample which was closed to 25 \( \mu m \) width. It gives a secondary source with a horizontally coherence length of 79 \( \mu m \). The maximum observable fringe distance is obviously given by the aperture of the hologram which is determined by the numerical aperture of the zone plate delivering the reference wave.

**EXPERIMENTS**

The 'beam splitting' Fresnel zone plate (FZP) had the following characteristic parameters: height of the individual gold zones 1.15 \( \mu m \), radius of the central zone of 7.8\( \mu m \), width of the outermost zone 0.3\( \mu m \). It was made by X-ray lithography on a SiN substrate. The FZP has 200 zones giving a full aperture of 200\( \mu m \). At 14.4keV the focal spot of the FZP was at \( f = 0.72 \, m \) and the diffraction efficiency was 8 \%. The geometry of the setup is schematically shown in Fig.1. The object is directly illuminated by the transmitted beam (zero order diffracted beam). At the same time the reference wave is formed by the first order diffracted beam. The object under investi-
gation is placed close to the reference source. The zero and higher than first order diffracted portions were removed by a pinhole placed 5 mm before the sample. The hologram was detected at a distance of x=2.7 m behind the sample using a high resolution CCD camera. The effective pixelsize in the arrangement was 1 μm and the exposure time for each hologram was two minutes. The X-ray hologram was converted into light by a thin scintillator screen and the image was magnified by a microscope and recorded on a CCD-camera.

Fig. 2 shows the hologram which was observed using a vertical wire of 5 μm diameter as a sample. The sample has a distance of 5 μm from the reference source. The central hologram part is overexposed to the direct beam. The concentric circles are the hologram of the 50 μm pinhole and the hyperbola-shaped interference fringes on both sides of the overexposed central part are the hologram of the wire itself. The fringe distances are different for the left and the right side, 21 μm and 68 μm, respectively, which corresponds to object distances of 3.4 μm and 11 μm. The large fringe spacing belongs to the wire side which is close to the reference beam whereas the small fringe spacing belongs to the opposite side of the wire.

\[\text{FIGURE 2. a) Fourier transform hologram of a 5 μm tungsten wire. The wire is vertically oriented and placed 5 μm beside the focal spot of the Fresnel zone plate. The width of the circular hologram is 680 μm (black is high intensity) b) Horizontal intensity profile through the centre of image a)}\]

As a more complex test object a gold grid with 15 μm grid spacing and 3.5 μm width of the grid lines was used. The fine grid was adjusted in a way that the reference wave could pass an empty square of it. A 100 μm pinhole was used for background suppression and the reference source was about 10 μm from its border. The numerical reconstruction was done after flatfield correction and background subtraction. The influence of the zero order radiation which passes the pinhole in the central part of the hologram was diminished by numerically cutting all values above a certain threshold value.

The result of the inverse Fourier transform is shown in Fig. 3b. The two slightly overlapping circles represent the image and the corresponding twin image of the 100 μm pinhole with the grid inside. The region of overlap of the image with the twin image corresponds to the distance of the reference source to the edge of the pinhole. From the effective pixel size of the camera and the pixel size in the reconstruction
which was determined from the known object size follows a effective demagnification by a factor of 0.9.

![Image](image1.png)

**FIGURE 3.** a) Fourier transform hologram of of a grid structure. The part of $0.5 \times 0.5\text{mm}^2$ which corresponds to $900 \times 900$ pixels was used for reconstruction. b) numerical reconstruction of the hologram in a) by applying inverse Fourier transformation. The $500 \times 500$ pixels central part is shown corresponding to $280 \mu\text{m}$ in the object plane.

**SUMMARY AND OUTLOOK**

Fourier transform holograms with hard X-rays recorded at an ESRF undulator beamline were successfully numerically reconstructed. Due to the geometry of the experiment especially the relatively small distance between sample and hologram plane there was no magnification effect and the final resolution was below the resolution of the used detector. For the near future, experiments are planned that allow larger magnification and investigation weak absorbing phase objects.

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**REFERENCES**