Multidirectional X-ray Dark-field Imaging With Two-dimensional Gratings

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Abstract. The two-dimensional (2D) X-ray grating interferometer uses gratings structured in the two transverse dimensions and, in this way, gives access to the dark-field and the differential phase signal in four directions of the image plane without the need to rotate the interferometer or the sample. In this paper, we discuss the potential of 2D X-ray grating interferometry for multidirectional dark-field imaging and we present experimental results obtained with this device.

Keywords: X-ray Grating Interferometry, X-ray Dark-field Imaging, Small-angle X-ray Scattering, Two-dimensional Gratings, X-ray Phase-contrast Imaging

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INTRODUCTION

X-ray grating interferometry (XGI) was first experimentally reported a decade ago as has since become a highly sensitive phase-contrast imaging technique [1, 2]. A standard grating interferometer is formed by two line gratings placed one behind the other in the beam path. A phase grating G1 generates a line interference pattern with high contrast at specific distances along the optical axis. A sample placed close to G1 induces distortions of this pattern which are analyzed with an absorption line grating G2. This analysis yields information on the optical properties of the sample, including the differential phase image and the absorption image [3].

The advantages of XGI over other phase-sensitive methods include good tolerance to curved and/or polychromatic X-ray beams, and a simple and compact setup. For these reasons, XGI can be adapted relatively easily to laboratory X-ray sources [4].

An important step in the development of XGI was made in 2008, when Pfeiffer et al. showed that, not only the differential phase image, but also a ‘small angle X-ray scatter’ image can be accessed with XGI [5]. This image is formed by the ‘blurring’ of the interference pattern from G1 caused by features at the micrometre and submicrometre length scale. Because of the analogy of this scattering signal with images obtained in visible-light and electron microscopy, the XGI scatter images are called ‘dark-field’ images. While the physical mechanism behind absorption and phase contrast image formation is well known, a formalism which describes the signal in the dark-field images is still under development [6, 7].

Standard XGI gives the component of the differential phase and dark-field signals

orthogonal to the grating lines; this means that the sensitivity of this device depends on the orientation of the features with respect to the grating lines: features causing wavefront distortions parallel to the grating lines cannot be revealed by the standard XGI.

Jensen et al. [8, 9] developed a method which consists in collecting dark-field images for different relative orientations of the sample with respect to the interferometer. These images can be suitably combined to yield directional dark-field images, maps of scattering strength and of degree of anisotropy of the features in the sample.

In this paper, we show how a 2D interferometer formed by 2D gratings can be used to access multidirectional dark-field images of the sample without the need to rotate sample or interferometer.

THE 2D GRATING INTERFEROMETER

The 2D grating interferometer uses gratings G1 and G2 which are structured in both transverse dimensions x and y . A 2D interferometer consisting of a 2D checkerboard diffraction grating with phase π -shifting structures and a mesh-type 2D analyzer grating is shown in Fig. 1 [10, 11, 12, 13].

FIGURE 1. Schematic representation of the 2D interferometer and raw interferogram recorded during a raster phase-stepping scan. Arrows on the raw interferogram indicate the sensitivity directions.

In this interferometer, the period P_2 of G2 is half of the period P_1 of G1, i.e. $P_1 = 2 \times P_2$, and the gratings are preferably separated by a distance D_n [11, 12, 13]:

$$D_n = n \frac{P_1^2}{8\lambda} . \quad (1)$$

In the above equation, λ is the wavelength of the radiation and n is an odd number. At the distances D_n , the interference pattern generated by G1 shows maximum contrast and can be approximated as a 2D sinusoid [11, 13]. From the analysis of the distortions of this interference pattern caused by the sample, differential phase images and dark-field

images can be retrieved in four directions, i.e. along the main axes x and y and along the two diagonals $d1$ and $d2$ (see Fig. 1). Moreover, the conventional absorption image can also be accessed from this analysis.

The phase-stepping technique can be used for this analysis; it consists in acquiring images at different transverse positions of one of the two gratings and it does not affect the spatial resolution of the imaging system. The direct analysis of the 2D moiré pattern can be used, instead of the phase-stepping method, to obtain image signals with a single exposure. However, in this case, the spatial resolution is limited by the period of the moiré pattern [14].

The phase-stepping scan is performed in two dimensions along the transverse coordinates x_g and y_g over at least 1×1 absorption grating period in at least 3×3 steps per period. During this raster phase-stepping scan, each detector pixel records a 2D intensity distribution $I(x_g, y_g)$ which is the convolution of the interference pattern incident on this pixel with the transmission function of G2; $I(x_g, y_g)$ is thus a 2D sinusoidal function.

The pixel-wise analysis of $I(x_g, y_g)$ measured with the sample in the beam path and corrected with the reference scan (no sample in the beam) yields the absorption, the differential phase and the dark-field signals. In this paper, we concentrate on the dark-field signal v which is calculated as the decrease, caused by the sample, in the contrast of $I(x_g, y_g)$. Depending on the nature and on the orientation of the scattering structures, the decrease in contrast may be isotropic or may be oriented along one preferential direction. For example, a region with nanoporosity will cause an isotropic decrease of contrast, while fibers or cracks parallel to the x axis will decrease the contrast of the interference pattern mainly along y .

The dark-field signals can be extracted with the 2D Fourier analysis of $I(x_g, y_g)$ which can be written in a 2D Fourier series as

$$I(x_g, y_g) = \sum_{l,m} a_{l,m} \cos \left[\frac{2\pi}{P_2} (lx_g + my_g + \phi_{l,m}) \right], \quad (2)$$

where $a_{l,m}$ are the Fourier coefficients and $\phi_{l,m}$ are their phases. If the phase-stepping scan is performed over $k \times k$ periods, the dark-field signals are given by [11]

$$v_x = A^{-1} a_{k,0}^{\text{sam}} / a_{k,0}^{\text{ref}} \quad v_y = A^{-1} a_{0,k}^{\text{sam}} / a_{0,k}^{\text{ref}} \quad (3)$$

$$v_{d1} = A^{-1} a_{k,k}^{\text{sam}} / a_{k,k}^{\text{ref}} \quad v_{d2} = A^{-1} a_{-k,k}^{\text{sam}} / a_{-k,k}^{\text{ref}}. \quad (4)$$

The term A^{-1} in the above equations corrects for the absorption of the sample: $A = a_{0,0}^{\text{sam}} / a_{0,0}^{\text{ref}}$ is the conventional absorption signal and the superscripts indicate values measured when the sample is in the beam path (“sam”) and measurements from the reference phase-stepping scan (“ref”).

EXPERIMENTAL RESULTS

The experiment was performed at the beamline ID19 of the European Synchrotron Radiation Facility [15]. The first grating was placed at approximately 150 m from the

wiggler source. An X-ray energy of 23 keV was selected by a Si-111 double crystal Bragg monochromator. The detector was a lens-coupled scintillator-CCD system with an effective pixel size of $7.5 \times 7.5 \mu\text{m}^2$.

The π -checkerboard phase grating was realized with two crossed π -shifting line gratings, each with period $P_1 = 4.785 \mu\text{m}$. Similarly, the mesh-type absorption grating was realized from two crossed line absorption gratings, each with a period of $P_2 = 2.4 \mu\text{m}$ [11, 13]. However, genuine 2D grating structures can now be made to realize both the phase grating G1 [13] and the analyzer grating G2 [16]. The distance between the two grating pairs was set to 480 mm, which corresponds to D_9 in Eq. 1.

FIGURE 2. Dark-field images of a lizard; bones and scales have strongly oriented scattering edges. All the images are displayed with the same linear colorscale from 0 (strong scattering, dark pixels) to 1.1.

The phase-stepping scans were performed over 1×1 period in 4×4 points, the exposure time per detector frame was 1 s. The visibility of the reference beam measured with this 2D interferometer was $a_{1,0}^{\text{ref}}/a_{0,0}^{\text{ref}} \approx 35\%$ along x , $a_{0,1}^{\text{ref}}/a_{0,0}^{\text{ref}} \approx 37\%$ along y and $a_{1,1}^{\text{ref}}/a_{0,0}^{\text{ref}} \approx a_{-1,1}^{\text{ref}}/a_{0,0}^{\text{ref}} \approx 10\%$ along the two diagonals [11]. The different visibilities

along x and y reflect the asymmetry of the source, which has an ellipsoidal shape elongated along x . The lower visibility along the diagonals, which also leads to a lower signal-to-noise ratio in the images in those directions, is discussed in Ref. [11].

The potential of this instrument for multidirectional dark-field imaging is demonstrated here with measurements on a lizard. The dark-field images along the four directions are shown in Fig. 2 (a)-(d); the sensitivity directions are indicated with arrows. Enlarged views of the regions surrounded by rectangles are displayed in Fig. 2 (e)-(h). These figures clearly show the complementarity of the information provided by the dark-field signal in the different directions.

FIGURE 3. (a) Four dark-field signals of Fig. 2 (a)-(d) mapped on the same image as described in the main text. (b) False-color image combining the dark-field signal along x (red channel) and the dark-field signal along y (green channel).

The dark-field images obtained with the 2D interferometer are inherently registered; by taking, for each pixel, the strongest signal over the four directions, all scattering details can be mapped in the same image as shown in Fig. 3 (a). The false-color image in Fig. 3 (b) visualizes the preferential scattering direction of the features in the sample as a combination of the dark-field images along x (red channel) and along y (green channel). The resulting yellow parts are features which scatter in both directions with similar intensity.

More sophisticated and accurate algorithms, such as the method proposed by Jensen et al. [9], can be used to process the four dark-field images obtained with the 2D interferometer.

CONCLUSIONS

Directional dark-field imaging can be performed with a 2D grating interferometer which yields, from a single raster phase-stepping scan, dark-field images along four directions 45° apart. The multidirectional information obtained with the 2D interferometer remains less accurate than the one accessible with previously developed techniques based on the

1D device [8, 9] which can measure dark-field signal in many directions of the image plane. However, the method proposed here does not require the rotation of the sample or the interferometer around the optical axis.

Since the 2D grating interferometer can be implemented at synchrotron facilities as well as at laboratory sources, the multidirectional dark-field signal obtained with the 2D interferometer can be advantageous in many field, such as medical imaging and materials science.

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