Quantitative Phase Imaging and Tomography with Polychromatic X Rays

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We have developed a grating interferometer for hard x-rays. The instrument consists of a phase grating acting as a beam splitter and an absorption grating. The recorded signal on the detector is essentially the first derivative of the projected x-ray refractive index in the direction perpendicular to the grating lines. The refractive index can be reconstructed by simple integration. For absorbing samples, the contribution of absorption contrast to the signal can be completely separated from the phase signal by applying a phase-stepping technique. The device can be operated with broadband radiation, such as a "pink" synchrotron beam. It was possible to distinguish materials with differences in refractive index of only a few percent. The method is expected to have wide applications in imaging of low absorbing samples such as biological and medical tissue or fibre reinforced polymers.

KEYWORDS: phase contrast, interferometry, hard x-rays, grating, medical imaging, tomography, radiography

1. Introduction

X-ray radiographic absorption imaging of such important classes of samples as biological tissue, polymers, and fiber composites is problematic, because these objects show only weak absorption. However, the cross section for elastic scattering of hard X rays in matter, which causes a phase shift of the wave passing through the object of interest, is usually much greater than that for absorption. For example, 17.5-keV X rays that pass through a 50 µm thick sheet of biological tissue are attenuated by only a fraction of a percent, while the phase shift is close to π. Recording the X-ray phase shift rather than only the absorption thus has the potential of substantially increased contrast. Consequently, various phase-sensitive X-ray imaging methods were developed in the past years 1-2). They can be classified into interferometric methods 3-5), techniques using an analyzer crystal 6-8), and free-space propagation methods 9-11). These techniques differ vastly in the nature of the signal recorded, the experimental setup, and the requirements on the illuminating radiation (especially its spatial coherence and monochromaticity). Although some of them yield excellent results for specific problems, none is very widely used. In particular, none of them has so far found application in medical diagnostics, which requires a large field of view of many centimeters, the efficient use of broadband radiation as provided by laboratory X-ray generators, and a reasonably compact setup. The use of gratings as optical elements in hard X-ray phase imaging can overcome problems that so far impair the wider use of phase contrast in X-ray radiography and tomography.

2. The grating interferometer

First experiments with X-ray grating interferometers were reported recently 12-15). Here we demonstrate quantitative two- and three-dimensional phase reconstruction with radiation of a bandwidth up to 5%, using highly efficient gratings. The interferometer consists of a phase grating G1 (i.e., a grating whose lines show negligible absorption but substantial phase shift) and an amplitude analyzer grating G2 (Fig. 1a). This type of interferometer was first proposed by us in 2002 12). The first grating acts as a beam splitter and divides the incoming beam essentially into the two first diffraction orders, which form a periodic interference pattern in the plane of the analyzer grating. Neither the period nor the lateral position of these fringes depends on the wavelength of the radiation used. Perturbations of the incident wave front induced by refraction on an object in the beam, lead to local displacement of the fringes. The analyzer grating acts as a transmission mask for the detector and transforms local fringe position into signal intensity variation (Fig. 1b). The detected signal profile thus contains quantitative information about the phase gradient of the object. Figure 2 shows scanning electron micrographs of cross sections through the gratings used. The height of the 4 µm period phase grating was chosen to give π phase shift for 17.5 keV radiation. The height of the gold absorbers in the analyzer grating is 12 µm, which results in a transmission of less than 10% at this energy.

To separate this phase information from other contributions to the signal, such as absorption in the sample, inhomogeneous illumination or imperfections of the gratings, a phase-stepping approach used in visible-light interferometry 16) was adapted to this setup. One of the gratings is scanned in the direction x perpendicular to the grating lines over one period of the grating, and for every point of the scan an image is taken. The intensity signal I(x,y) in each pixel of the detector plane oscillates as a function of the grating position. The phases ϕ(x,y) of the intensity oscillations in each pixel are related to the wave-front phase profile φ(x,y), the X-ray wavelength λ and the period g of the absorption grating and the distance ∆ between the two gratings by

\[ \varphi = \frac{\lambda \Delta \phi}{g} \]
\( \phi(x,y) \) contains no other contributions, particularly no absorption contrast. The phase profile of the object can thus be retrieved from \( \phi(x,y) \) by a simple one-dimensional integration. By performing the same phase stepping scan with the object removed from the beam, a phase flat field \( \phi_{\text{flat}}(x,y) \) can be obtained. It contains all distortions of the incident wave fronts and of the gratings, and it can be used for correction by subtracting the phase flat field. This greatly reduces the precision requirements of the grating fabrication.

3. Phase contrast radiography

The described method was applied to image an animal organ, a rat heart, which was placed in a container filled with a 4% aqueous formalin solution. We used the pink beam from the wiggler source at beam line 4S of the Swiss Light Source. A 100 µm Zr filter and a mirror was used to suppress all radiation above 18 keV photon energy. The detector consisted of a YAG:Ce scintillator optically coupled to a CCD camera. Due to the absorption edge of Y at 17 keV, radiation below 17 keV energy was recorded only with very low efficiency, so that essentially a band with a width of 1 keV around a mean energy of 17.5 keV was used for imaging.

Figure 3 shows the absorption and phase image of the sample. Due to the limited size of the synchrotron beam of 3 mm, the image has been stitched together from 20 sub-frames. In absorption contrast, only air bubbles and some fatty tissue are visible, whereas the complete organ with many details can be seen in the differential phase contrast image.
3. Phase contrast tomography

As mentioned before, the phase gradient images can be used to obtain phase images by integration. As the method yields quantitative information, a set of projections taken from an object under different viewing angles can be used to obtain a 3-dimensional map of the real part $\Re$ of the complex refractive index $n = 1 - \delta + i\beta$ for each voxel. Due to dispersion, $n$ changes with photon energy. When using polychromatic radiation, the reconstructed phase projections and tomograms will be quantitative, showing the distribution of the refractive index averaged over the photon-energy band.

Figure 4 shows processed absorption and phase projection images, as well as reconstructed tomograms, of a reference sample made of two polymer fibres (polyamide, PA, and polybutylene terephthalate, PBT) and a boron fiber with a tungsten core, acquired with broadband radiation of $(17.5 \pm 0.5)$ keV photon energy. (a) Noninterferometric projection image. (b) Tomographic slice, corresponding to the position indicated by the horizontal line in (a). (c) Reconstructed phase projection. (d) Tomographic slice through the refractive-index distribution. (e,f) Section profiles through the fiber centers in, respectively, the non-interferometric tomogram (e) and the phase tomogram (f) (solid: B/W, dashed: PA, dash-dotted: PBT, dotted: literature values).

4. Conclusion

The experimental results show that a grating interferometer can be used for qualitative or quantitative two- and three-dimensional X-ray phase radiography. The moderate requirements on coherence and monochromaticity, the possibility to make large gratings of high quality and efficiency, suggest that hard X-ray phase imaging with grating interferometers can find application in areas where phase imaging would be desirable, but is currently not widely used. In particular, the possibility to combine the instrument with imaging systems of a large field of view and the efficient use of broadband sources let us envisage applications in such fields as medical and biological imaging or research on organic materials.

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