INSTITUTE OF PHYSICS PUBLISHING JOURNAL OF PHYSICS D: APPLIED PHYSICS
J. Phys. D: Appl. Phys. **36** (2003) A65–A68 PII: S0022-3727(03)60123-3

Two-dimensional x-ray magnification based on a monolithic beam conditioner

D Korytár[1,6], P Mikulík[1], C Ferrari[2], J Hrdý[3], T Baumbach[1], A Freund[4] and A Kuběna[5]

[1] Fraunhofer Institut IZFP EADQ, Krügerstrasse 22, D-01326 Dresden, Germany
[2] IMEM CNR, Parco Area delle Scienze 37/A, Fontanini, I-43010 Parma, Italy
[3] Institute of Physics, CzAS, Na Slovance 2, CZ-18221 Praha 8, Czech Republic
[4] European Synchrotron Radiation Facility, BP 220, F-38043 Grenoble, France
[5] Institute of Condensed Matter Physics, Faculty of Science, Masaryk University Brno, Kotlářská 2, CZ-61137 Brno, Czech Republic

Received 14 September 2002
Published 22 April 2003
Online at stacks.iop.org/JPhysD/36/A65

Abstract
In x-ray imaging and beam conditioning it is useful to magnify or demagnify the x-ray beam, or an image, approaching (sub)micrometre resolution or the (sub)micrometre illuminated region. Using an asymmetric diffractor it is possible to expand or compress the x-ray beam in one direction. Combining two such diffractors with mutually perpendicular planes of diffraction even two-dimensional beam expansion or compression can be obtained and, for suitable wavelengths, it is even possible to design and cut a single crystal in such a way that it works as a monolithic device expanding or compressing the x-ray beam in two directions. In this paper, a new magnifying monolithic optical device for a two-dimensional magnification of 25 at 10 keV, based on two noncoplanar asymmetrically inclined $\{311\}$ diffractors, was designed and made from a single silicon crystal. A ray-tracing image has been simulated to check the functionality of the device. The experimental testing of this device was performed at Optics beamline BM5 at ESRF Grenoble. An undistorted image magnification of about 15 was achieved at a photon beam energy of 9.6 keV. When the photon energy was increased, a higher magnification and increased distortion were observed (horizontal magnification of 39, vertical magnification of 20) at an energy of 10.045 keV. The advantages and disadvantages of the device, as well as further steps to improve it are briefly discussed.

1. Introduction

New, hard x-ray imaging techniques developed at third generation synchrotron radiation (SR) sources have been extensively studied utilizing various optics and experimental settings [1, 2]. Three of the optics—phase zone plates [3], parabolic compound refractive lenses [4] and an x-ray waveguide [5]—have demonstrated submicrometre resolution.

The importance of perfect crystal asymmetric diffractors (by a diffractor we mean the physical part of a crystal used to diffract the incoming x-ray beam) as one-dimensional optical elements for coherent x-ray beams has been confirmed both theoretically and experimentally [6, 7]. These diffractors can increase (decrease) the lateral coherence length with a simultaneous decrease (increase) of the flux. Their other well-known property is the image expansion or compression in one dimension. The potential applications of Bragg diffraction optics based on asymmetric inclined diffractors have been evaluated as well [8].

The possibility of combining two asymmetric diffractors with mutually perpendicular planes of diffraction and thus obtaining two-dimensional image magnification was first demonstrated by Boettinger *et al* [9]. Using this set-up Kuriyama *et al* [10] obtained a resolution of 1.2 μm. The observed Fresnel diffraction effects were then quantitatively studied and the set-up was also used to perform three-dimensional image magnification by means of computed tomography (see [11] and references therein). Recent

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[6] Permanent address: Institute of Electrical Engineering, SAS, Vrbovská 110, SK-921 01 Piešt'any, Slovakia.

calculations by Spal give a resolution as low as 0.3 μm for this kind of x-ray holographic microscopy [11].

Another system for two-dimensional optics, based on two independent $(n, -n)$ couples of asymmetric Bragg diffractors and adjusted to have perpendicular planes of diffraction, was developed at the Hyogo beamline at Spring 8. They obtained a resolution of 2 μm in absorption and 15 μm in phase contrast [12]. Live magnified images of living objects have been obtained [13].

Spatially resolved diffractometry, using asymmetrically cut analyser crystals, (polylithic device) has recently been successfully performed by Köhler *et al* [14] at the beamline ID 11 at ESRF. A similar polylithic instrument devised by Stampanoni *et al* [15] to achieve a submicron resolution was constructed and is now being tested.

The advantages of monolithic counterparts of this type of devices are compactness, thermomechanical stability and short distances for the beams to pass between individual diffractors [16]. The drawbacks include complex preparation and noncompatibility with planar polishing technologies. The analytical solution to the problem of finding a pair of surfaces that produce distortion-free images was given in [17]. A monolithic system based on two noncoplanar asymmetric inclined diffractors {440} was first applied to SR at Daresbury Laboratory (two-dimensional magnification of 6) [18].

The aim of this paper is to present a design for a new magnifying monolithic x-ray optical device for 10 keV SR. We discuss results obtained during the testing of this diffractor at an energy range of around 10 keV, using radiography of a regular grid object, in order to evaluate the performance (magnification, resolution) of the device.

2. Experimental

A high resistivity floated zone (111) silicon crystal was used to cut the new magnifier. It was devised so as to obtain a magnification of 25 for a 10 keV beam and is based on two noncoplanar asymmetric inclined {311} diffractors. Figure 1 shows a three-dimensional model of the crystal with the active surfaces and with the incident, first and second time diffracted (outcoming) beams for two energies of 8 and 10 keV (the latter giving a higher asymmetry and magnification). In the case of x-ray magnification the x-ray beams pass from the right to left. The direction of the beams is reversed in the case of beam demagnification or compression. A computer simulation, based on plane waves and the two-beam dynamical theory of x-ray diffraction, gives a magnified undistorted image for such a system of diffractors (figure 2). From the experimental point of view it was suggested that this device be tested as a magnifying system first because it is easier to adjust and evaluate the imaging properties, especially the resolution. An in-house Si(111), Si(−1−1−1) vertical monochromator was used to choose the energy at Optics beamline BM5 at ESRF. An in-house horizontal plane goniometer with one vertical and two horizontal axes was used to adjust the crystal. The experimental procedure consisted of the following three steps:

(a) The first diffraction (311) was adjusted, see figure 1, into the horizontal plane of the goniometer by means of an x-ray eye, to find the simultaneously diffracted beam of the diffraction (42−2) (= (311) + (11−3)) by means of a CCD camera, and to find the twice successively diffracted and expanded beam at an energy below the optimal one (larger angle of incidence).

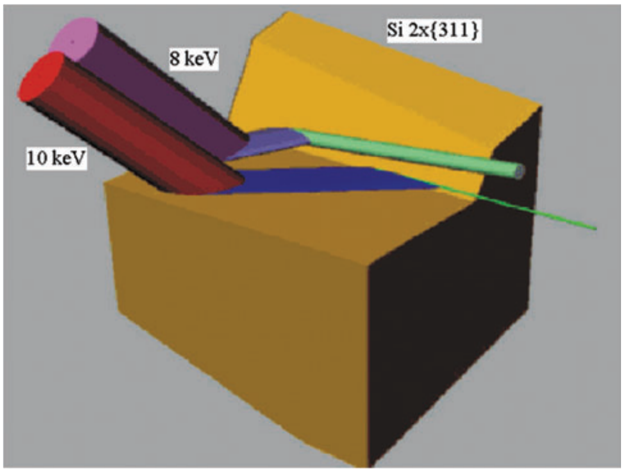

Figure 1. Design of a monolithic x-ray magnifier/demagnifier (magnification of 25 at the energy of 10.0 keV) with the incident and diffracted beams for two energies of 8 and 10 keV.

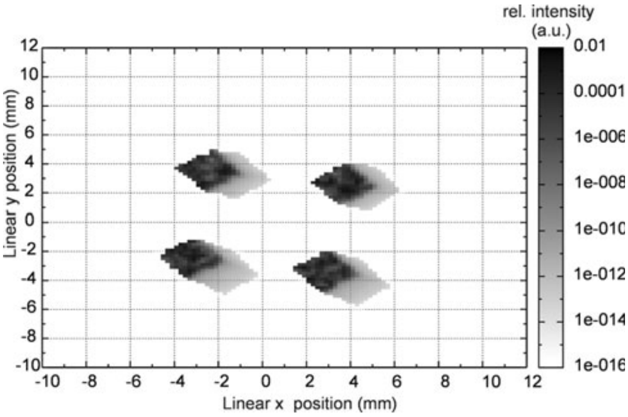

Figure 2. Ray tracing simulation results confirming the functionality of the device. We have obtained a magnification of 22 from an object composed of 0.1 mm × 0.1 mm squares 0.4 mm apart. A two-beam dynamical theory with plane waves has been used.

(b) The energy was increased to increase the magnification up to 25 at 10 keV, at which energy the magnified image should be undistorted.

(c) The energy was increased over 10 keV in order to increase the magnification to the limit at which the angle of incidence or exit of at least one of the diffractors goes below the angle of total reflection.

After the adjustment, magnified images of an absorbing grid were taken on a Kodak Industrex film positioned 3 cm over the second diffracting plane and developed in a standard way.

3. Results and discussion

Figure 3 shows a Cu #300 microscopic mesh (32 μm wide stripes and 64 μm wide windows), located 38 cm in front of the magnifier crystal, and its x-ray magnified image at 9.6 keV (magnification of 15). Figure 4 shows an Au microscopic

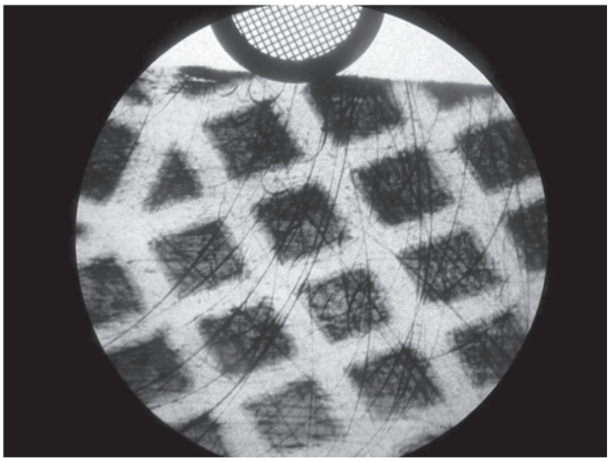

Figure 3. Microscopic Cu #300 mesh grid (upper grid) and its x-ray magnified image (lower grid): x-ray magnification of 15 at 9.6 keV. Grid diameter 2.3 mm, 32 μm wide stripes and 64 μm square windows.

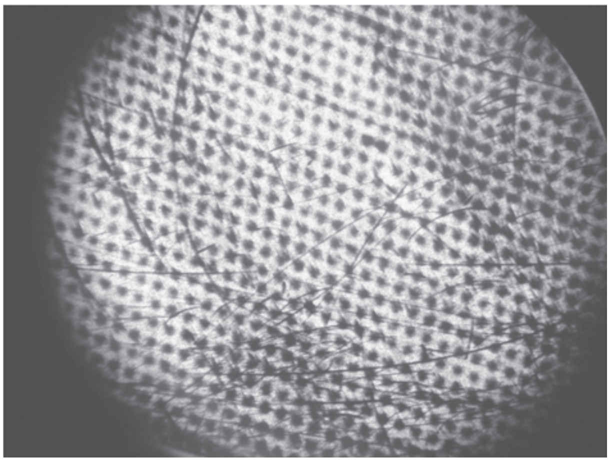

Figure 4. The x-ray magnified image of an Au #2000 mesh microscopic grid (4 μm wide stripes and 12 μm square windows): x-ray magnification of 15 at 9.6 keV.

#2000 mesh grid (4 μm wide stripes, 8 μm square windows) at the same energy. The scratches across the images are because the surfaces are not sufficiently polished. They should be removed by polishing for a longer time or by more efficient polishing.

The device was devised to give a magnification of 25 at a beam energy of 10.0 keV. After the first testing at 9.6 keV the beam energy was increased to 10.0 keV in order to increase the magnification. The image is distorted with two perpendicular magnifications of 33 and 18 at this energy. At the energy of 10.045 keV the image is even more distorted (magnifications of 39 and 20 in figure 5). At the energy of 10.122 keV no grid image was observed—supposedly, the angular precision of the active surfaces relative to crystallographic planes was not sufficient.

From the results obtained, it is obvious that the preparation of image-nondistorting monolithic devices for high magnifications (over 20) will require that the active surface be cut with a precision much better than 0.2°. Modern deterministic technologies of microgrinding of silicon will be the potential candidates for this purpose. As an alternative, the standard repetitive trial-and-error method of measuring, cutting and polishing requiring access both to an optical laboratory and to the beamline can be successful as well. This could also be a method of verifying theoretical values of the best achievable spatial resolution as given by Spal [11].

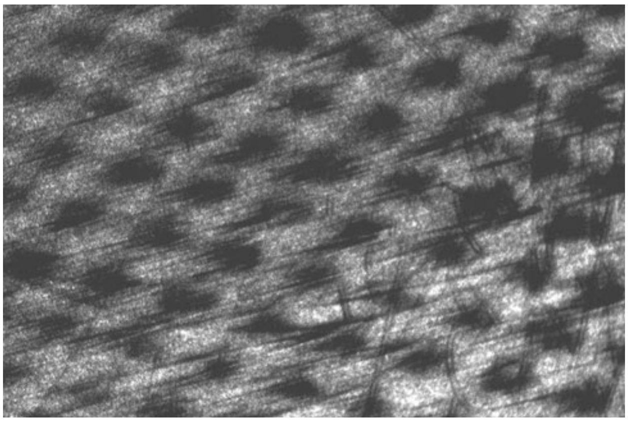

Figure 5. The x-ray magnified image of the Au microscopic #2000 mesh grid. The x-ray magnification in the horizontal direction is 39 and in the vertical direction is 20 at 10.045 keV.

The contrast at scratches at the active surfaces of the device indicates that kinematic scattering at imperfect surfaces is worth testing to obtain high throughput intensity. It was also suggested that the sample crystal and crystal film distances should be minimized to utilize the advantage of high thermomechanical stability of the device. For the adjustment, in addition to imaging detectors (x-ray eye, CCD camera), it will be necessary to use a scintillation detector to adjust the crystal to the peak intensity. From the point of view of the applicability of the device it becomes clear that the next planned version, which will produce the diffracted beam parallel to the incident one, will be much more interesting because of the ease of adjustment and compatibility with the equipment (Frelon camera working in the horizontal plane) of SR beamlines.

4. Conclusion

In conclusion, a new monolithic device with two noncoplanar diffractors for a magnification of 25 at 10 keV has been successfully adjusted and tested at ESRF. We conclude that in order to use these kind of devices routinely at synchrotron sources it is necessary to have the incident and outcoming beams parallel to each other. To increase the magnification and to approach the submicrometre resolution limit given by Spal will require higher precision of surface preparation and/or a trial-and-error technique to adjust the active surfaces of diffractors. The surface finish of the active surfaces should be optimized as well.

Acknowledgments

We wish to thank our colleagues Dr J Hoszowska, P Cloetens, I Snigireva, and A Snigirev, who helped us before and during the ESRF experiments. This work has been partially supported by the Slovak Grant Agency for Science (project No 2/1167/22). D Korytár and P Mikulík acknowledge support by Marie Curie Fellowships of the European Community, program ‘Growth’ (contract No G5TR-CT2000-00046) and ‘Human Potential’ (contract No MCFI-2000-00671), respectively.

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