Journal of
Synchrotron
Radiation

ISSN 0909-0495

Received 15 August 2007
Accepted 28 September 2007

Beam-shaping condenser lenses for full-field transmission X-ray microscopy

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A new type of diffractive X-ray optical elements is reported, which have been used as beam-shaping condenser lenses in full-field transmission X-ray microscopes. These devices produce a square-shaped flat-top illumination on the sample matched to the field of view. The size of the illumination can easily be designed depending on the geometry and requirements of the specific experimental station. Gold and silicon beam-shapers have been fabricated and tested in full-field microscopes in the hard and soft X-ray regimes, respectively.

Keywords: beam-shaper; Fresnel zone plate; diffractive optical element; flat-top illumination; X-ray microscopy.

1. Introduction

Full-field X-ray microscopy is a well established technique at many synchrotron light sources for the investigation of inorganic and biological samples. The key optical elements in full-field microscopes are a condenser to provide illumination of the sample and an objective lens to produce a magnified image of the sample on the detector. The illumination should be as homogeneous and intense as possible. Moreover, the numerical aperture should be matched to that of the objective lens in order to obtain optimum resolution (Born & Wolf, 1999).

Fresnel zone plates (FZPs) (Anderson *et al.*, 2000), tapered capillaries (Yin *et al.*, 2006), mirrors (Rau *et al.*, 2005) and combinations of these devices (Niemann *et al.*, 2003) are commonly used as condensers. However, these optics focus the beam into a spot, which is smaller than the field of view of the microscope. As a result they cannot provide a uniform illumination. This problem can be overcome by moving the condenser transverse to the direction of the beam during the exposure (Niemann *et al.*, 2003).

The use of beam-shapers with more complex optical functionality in the X-ray regime was first demonstrated by Di Fabrizio *et al.* (2003). However, the beam-shaper design is usually difficult since many unknown parameters of the beam have to be defined in advance and there are some restrictions owing to the fabrication limitations. Recently a simple approach of a beam-shaper design was proposed and tested with a soft X-ray full-field microscope (Vogt *et al.*, 2006). The idea of the design is to divide a conventional FZP into sectors, keeping the local spatial frequency within each sector constant. As a result, each sector will produce a flat-top illumination in the focal plane. However, even geometrically, a superposition of non-symmetric radially distributed shapes forms an approximately round illumination with significant ‘tails’.

In this paper we present an optimized design of such a beam-shaper based on square gratings. The shape of the produced illumination is square and can be designed to match the field of view of the microscope. Several beam-shapers were fabricated and tested in both soft and hard X-ray microscopes.

2. Design and fabrication

The design of the beam-shaping elements is based on a standard FZP. The original FZP is divided into square subfields, as shown in Fig. 1(*a*). Each subfield consists of a linear grating with constant line orientation and period, which correspond to the local orientation and period of the structures of the FZP. As a result, the beam-shaper has the same focal length as the FZP, and the first diffraction order of every subgrating will form exactly coinciding square illumination in its focal plane with the illuminated area equal to the size of the gratings. The advantage over the design shown by Vogt *et al.* (2006) is that one can avoid tails of the illumination, which increases the intensity in the uniformly illuminated area. Another advantage of using the square shape of illumination is that usually the active area of the detector is also square. In this case the illumination of the beam-shaper can be perfectly matched to the detector size.

We have fabricated beam-shapers of different dimensions, from 0.5 mm × 0.5 mm to 1.9 mm × 1.9 mm, with subfields of 50 µm × 50 µm or 35 µm × 35 µm and with the outermost grating periods down to 100 nm (50 nm lines and spaces). An example of a silicon beam-shaper, consisting of 400 subfields, is shown in Fig. 1(*b*).

Despite using the same design, different materials and nanofabrication techniques are required for producing beam-shapers for soft and hard X-ray applications in order to achieve better efficiency. In the case of hard X-rays the chosen material was gold, and 550–700 nm-thick structures were prepared by electroplating into a polyimide mould as described by Jefimovs *et al.* (2007). In the case of beam-shapers for soft X-rays the 350 nm-deep structures were etched

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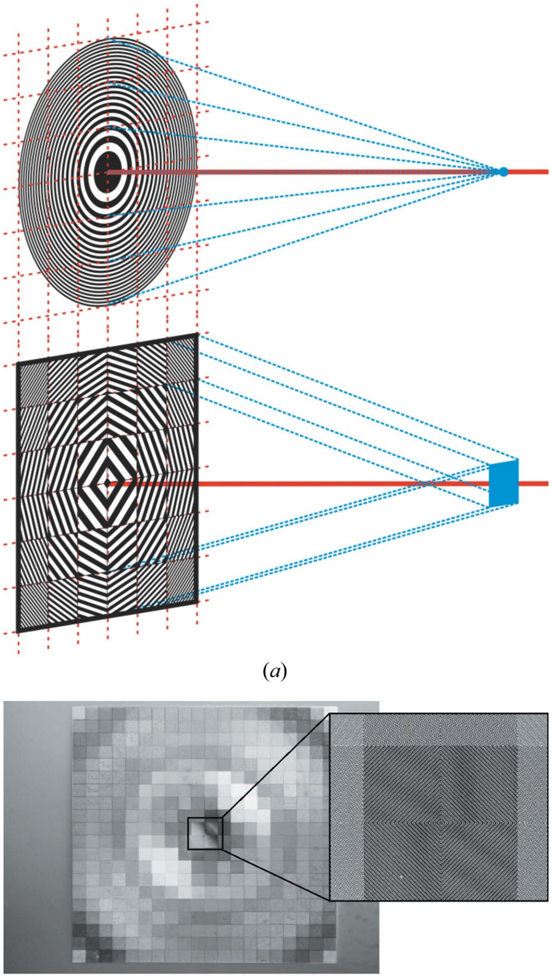
(*a*)

(*b*)

Figure 1
(*a*) Scheme showing the equivalence between a Fresnel zone plate and the beam-shaping condenser. (*b*) Optical microscope image and scanning electron microscope image of the central part (inset) of the silicon beam-shaper consisting of 400 subfields (50 µm × 50 µm). The outermost subgratings have a period of 100 nm.

directly into silicon membrane. Details of the fabrication process will be published elsewhere.

In order to block the zero order through the condenser an opaque square central stop must be used. For hard X-rays the central stop was introduced in the system as an independent element, while for soft X-rays it was evaporated through a square aperture on the back of the beam-shaper membrane.

Several parameters such as the size of the element, size of the subgratings, period in the outermost gratings and size of the central stop are easy to address during the design in order to fulfil geometrical conditions of the specific experimental station (beam size, focal distance, sample size, active area of the detector). For instance, the size of the shadow formed by the central stop can be matched by the size of the beam-shaper illumination magnified by the objective lens.

3. Results and discussion

We tested the performance of several beam-shapers at 500 eV, 720 eV and 8 keV. In addition, we performed a series of full-field microscopy imaging experiments in both soft and hard X-ray regimes. Examples of illumination from the beam-shaper and some full-field microscope images are shown in Fig. 2.

The hard X-ray (8 keV) experiments were performed at the TOMCAT beamline (Stampanoni *et al.*, 2006) of the Swiss Light Source (Villigen, Switzerland). Fig. 2(*a*) shows a typical intensity profile of the beam-shaper obtained with a high-resolution X-ray detector placed at its focal plane. One can see that the shape of illumination is square and the intensity variations in the flat-top illuminated area do not exceed 6%. The indistinct edges of the illumination are caused by the low monochromaticity of the beam (bandwidth of ∼2–3%) and the extended source size. The maximum measured gain was ∼82 for a 1.7 mm × 1.7 mm beam-shaper, which corresponds to an average diffraction efficiency of 7%. This beam-shaper was used as a condenser in full-field microscope set-up in combination with an objective FZP with an outermost zone width of 100 nm. Another FZP with an outermost zone width of 100 nm was used as an object. Fig. 2(*b*) shows the hard X-ray full-field microscope image obtained. One can see that the outermost 100 nm-wide zones are resolved.

In the soft X-ray regime, experiments were carried out at the TWINMIC experimental station at the BACH beamline (Zangrando *et al.*, 2001) of the ELETTRA synchrotron (Trieste, Italy) at 500 eV and 720 eV X-ray energy using a highly monochromatic beam. Several images of test patterns were taken, using the beam-shaper in a full-field microscopy set-up. A silicon FZP with an outermost zone width of 50 nm was used as objective lens. Fig. 2(*c*) shows an X-ray full-field microscope image of a Siemens star. The smallest resolved structures are around 70 nm. The bright spots near the edges of the image are caused by the first diffraction orders of the condenser subgratings, passing through the sample and the FZP without being diffracted (zeroth-order radiation). The central stop suppresses these spots in the field of view of the microscope. As seen from Fig. 2(*c*), the central stop shadow in the detector is perfectly matched with the size of the beam-shaper illumination, magnified by the objective lens. Unlike in the case of hard X-rays, the main problem in soft X-ray full-field microscopy with undulator source is the presence of speckles in the image. A similar problem was also noted by Vogt *et al.* (2006). The origin of the speckles is the long transverse coherence length of the irradiation. It exceeds the size of the subfields of the beam-shaper, and thus enables the diffracted beams from the neighbouring gratings to interfere in the focal plane of the beam-shaper. In order to reduce speckles, mechanical vibrations were introduced to the mirror upstream of the condenser. However, some remaining speckles, seen as grey vertical lines, remained on the image. We found that the contrast of the speckle pattern changes significantly even by a slight change of the condenser focal distance. The speckle contrast may be reduced by optimizing the relative phases of the waves from the individual subfields, as shown by Solak *et al.* (2002). Other possibilities for avoiding speckle are to use a diffuser (Kagoshima *et al.*, 2002) or to vibrate the condenser (Denbeaux *et al.*, 1999).

In conclusion, we designed and fabricated several beam-shaping condenser elements. The gold beam-shapers were tested with hard X-rays and the silicon beam-shapers with soft X-rays. The beam-shapers produce a square-shaped intense flat-top illumination in the focal plane. They were successfully used in imaging experiments with full-field X-ray microscopes.

This work was partly funded by EU project ‘Integrating Activity on Synchrotron and Free Electron Laser Science Contract’ under contract No. RII3-CT-2004-506008 part JRA3 and by ‘Departament d’Educació i Universitats de la Generalitat de Catalunya i del Fons

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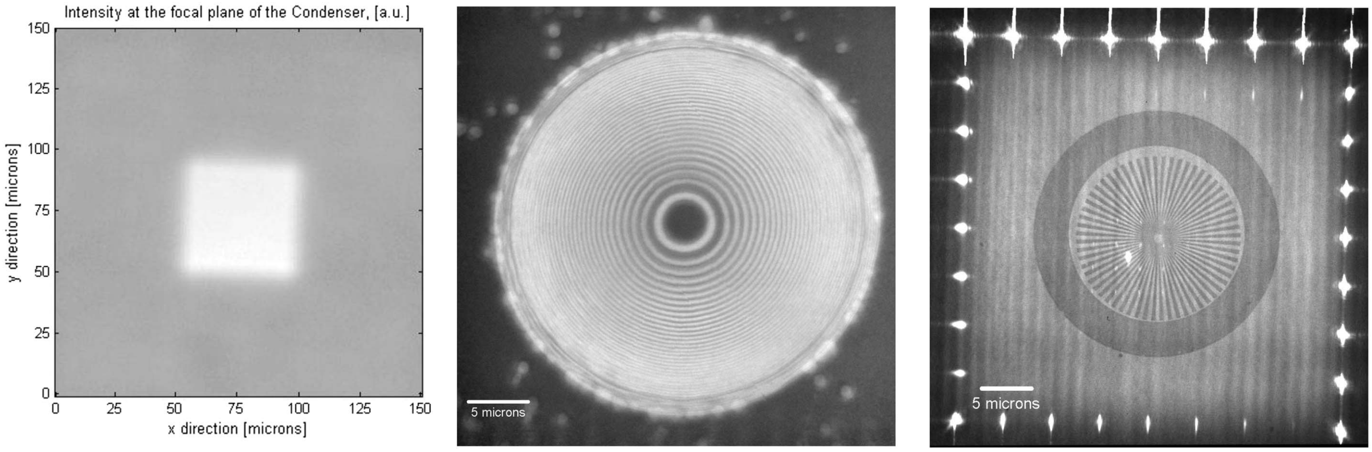

(*a*) (*b*) (*c*)

Figure 2
(*a*) Square-shaped flat-top illumination produced by a gold beam-shaping condenser lens in its focal plane at 8 keV photon energy. (*b*) Transmission X-ray microscope micrograph taken in the hard X-ray regime (8 keV) using a gold beam-shaping condenser lens. (*c*) Transmission X-ray microscope micrograph in the soft X-ray regime (720 eV) using a silicon beam-shaping condenser lens.

Social Europeu'. The X-ray experiments were performed at the Swiss Light Source and ELETTRA synchrotrons. We would like to thank Anja Weber for assistance during substrate preparation. We would like to acknowledge Federica Marone and Andreas Menzel (PSI) for their help at the TOMCAT beamline, as well as Gordan Mikuljan for his technical support during the experiment set-up.

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