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A rotating condenser and off-axis zone plate monochromator for the TXM at the undulator U41 at BESSY II

B. Niemann*, P. Guttmann, D. Hambach, G. Schneider, D. Weiß, G. Schmahl

Institute for X-Ray Physics (IRP), University Georgia Augusta at Göttingen, Geiststraße 11, D-37073 Göttingen, Germany

Abstract

The Göttingen transmission X-ray microscope at the low emittance electron storage ring BESSY II uses the concept of dynamical aperture synthesis (Reynolds, DeVelis, Parrent, Thomson (Eds.), The New Physical Optics Notebook, SPIE, 1990, pp. 536–548) for the object illumination. The concept is well suited as a condenser, as it can match *any* required numerical aperture of the TXM objective. Furthermore, a novel off-axis transmission zone-plate monochromator is included, which can generate a monochromaticity of several thousand in the object illumination. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: X-ray condenser; X-ray microscopy; Zone plate monochromator

1. Introduction

The transmission X-ray microscope (TXM) being installed and under test at the electron storage ring BESSY II in Berlin uses X-rays delivered by the undulator U41. The condensor–monochromator which performs the object illumination consists of an off-axis transmission zone plate (OTZ) monochromator and a pair of rotating mirrors [1–3] for dynamical aperture synthesis (DAS) [4].

2. The off-axis zone plate monochromator

Fig. 1 illustrates an OTZ linear monochromator as used at BESSY II. An OTZ with an area $2 \times 2\,\mathrm{mm}^2$ in size, located at $R = 17.55\,\mathrm{mm}$ from the zone plate center accepts the central beam of the strongly collimated undulator radiation at a distance of 30 m from the source. As characteristic for every linear monochromator the wavelength can be changed by moving the OTZ along its optical axis.

As the OTZ comprises only a very small part of the full zone plate pattern and the zone structures in the OTZ only represent a short arc, it can be regarded as a "focusing grating", which disperses the radiation one dimensionally (vertically) in the object plane 5 m downstream of the OTZ. The spectrum achieved in the object plane with the optical setup according to Fig. 2 extends some hundred μm in height and is of homogeneous intensity in the direction of dispersion. A monochromatic source image—imaging scale: 6 : 1—extends $\varsigma_{y,\mathrm{image,fwhm}} = 9\,\mu\mathrm{m}$ in the vertical and $\varsigma_{x,\mathrm{image,fwhm}} = 33\,\mu\mathrm{m}$ in the horizontal direction at realistic operating condition of BESSY II.

The direction of the smallest source diameter is oriented parallel to the direction of dispersion;

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*Corresponding author. Tel.: +49-551-395-063; fax: +49-551-399-430.

E-mail address: bnieman@gwdg.de (B. Niemann).

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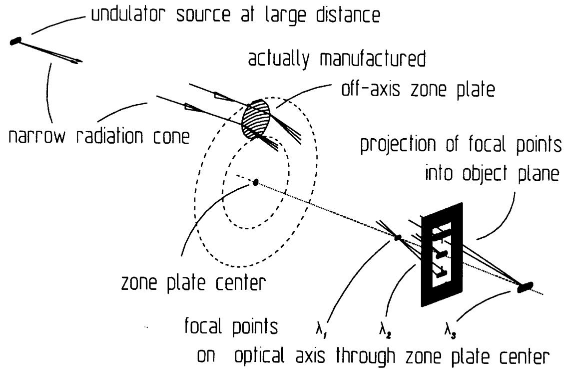

Fig. 1. Schematic of an off-axis zone plate linear monochromator. A small off-axis region of a zone plate, which can also be regarded as a focusing transmission grating, produces a series of monochromatic source images on the optical axis. The projection of these images into the object field is also sketched and results in a one-dimensionally dispersed spectrum of the source.

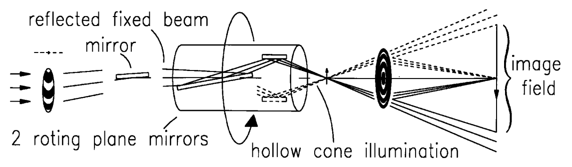

Fig. 2. Schematic of the RK-TXM including a rotating condenser matching the NA of the MZP. The small source size and the well collimated beam of the undulator source are of great advantage, as they allow to realize a high performance optical setup with comparatively small optical elements.

therefore, best monochromaticity is achieved in the monochromatic source image, as the monochromaticity only depends on the extension of the source in this direction. For comparison, in a zone-plate monochromator using a conventional on-axis condenser zone plate (CZP) with complete zones, as e.g. formerly used in the TXM at BESSY I—the monochromaticity was determined by the two-dimensional extension of the source, because the radiation was dispersed by the CZP in *two* dimensions. Furthermore, this led to a comparatively inhomogenous intensity distribution with a strong maximum in the center. In these two respects an OTZ linear monochromator is superior to any on-axis CZP linear monochromator.

With the OTZ mentioned above a monochromaticity of $\lambda/\Delta\lambda \approx 2000$ can be achieved in the monochromatic source image of $\varsigma_{y,\mathrm{image,fwhm}} = 9\,\mu\mathrm{m}$ height. Object illumination with higher spectral resolution is obtained, if an off-axis area farther away from the zone plate center is selected for the manufacture of the OTZ.

3. The rotating condenser

Fig. 2 illustrates how the OTZ linear condenser-monochromator can be used to perform a dynamical aperture synthesis (DAS) with the help of a rotating condenser (RK), which contains two short rotating mirrors, located very close to the object plane to be illuminated [1,3]. The inclination angle of the second rotating mirror performs the matching of the required numerical aperture.

The reflection planes of both mirrors—defined by the vectors of the incoming and the reflected beams—have to be parallel if the incoming beam is supposed to propagate parallel to the axis of rotation. A deviation from parallelism blurs the size of the monochromatic image during rotation and thus degrades the monochromaticity. In our design a deviation of a few tenths of a mrad is tolerable.

4. Imaging performance

The DAS of a narrow hollow cone illumination has several advantages. The image field can be increased, as the shadowed region inside the illuminating solid angle is larger. The depth of focus increases by at least a factor of two compared to full cone illumination as the angular sequence of the individual images is recorded with very narrow illuminating condenser beams. The image will be free of coherent noise as obtained with ordinary incoherent imaging systems even with coherent X-ray sources, as the principle of time-sequential recording and intensity superposition in the image destroys the edge ringing present in the individual images.

A theoretical model describing the image performance of a TXM using a rotating condenser

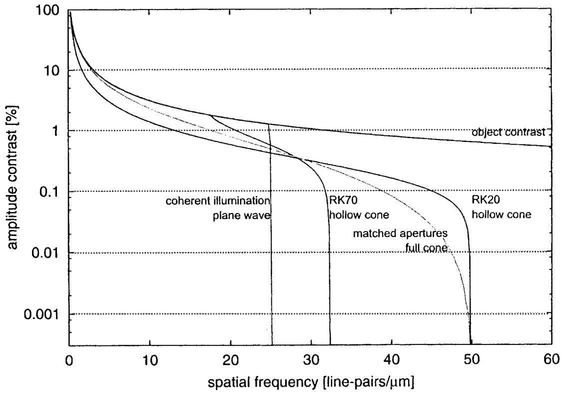

Fig. 3. Amplitude image contrast achieved with different condenser arrangements when imaging a model protein grating at 2.4 nm wavelength with a micro objective of about 25 nm Rayleigh resolution. Best resolution is obtained with RK20. By definition, a rotating condenser RK20 (RK70) just matches a numerical aperture of a micro objective with a smallest, outermost zone width of 20 nm (70 nm) at the regarded wavelength.

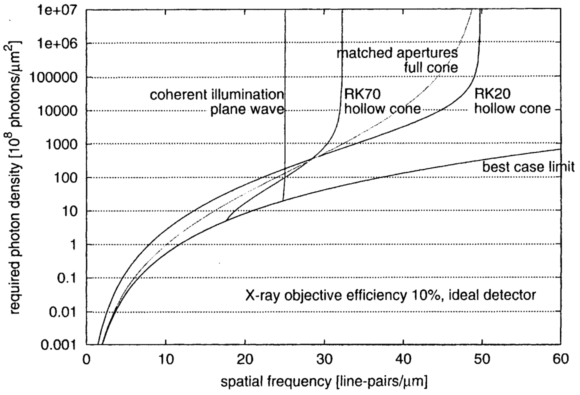

Fig. 4. Required photon number to image a model protein grating at 2.4 nm wavelength in the amplitude contrast mode with a micro objective of about 25 nm Rayleigh resolution. The numbers achievable with different condenser arrangements are plotted. The high resolution arrangement RK20 requires highest photon numbers at low spatial frequencies, as due to the matched numerical apertures of condenser and objective about half the intensity diffracted by the object cannot be transmitted by the objective.

was established [5]. It assumes that protein fibers of infinite length and a square cross-section d^2 form a grating with a period of $2d$. The fibers are embedded in water or ice and are imaged in a TXM with an X-ray objective of about 25 nm Rayleigh resolution. In Fig. 3 the upper graph shows the contrast which is generated by the fibers and observable *directly behind it*. It is plotted as a function of the parameter $1/2d$. The other graphs show the contrast obtainable in the *image* plane for different condenser setups using the given X-ray micro objective.

For comparison, the imaging quality is also shown for other illumination conditions without rotating condenser. If on-axis plane waves illuminate the object we get coherent imaging. The contrast can be retained fully up to the cut-off frequency of 25 LP/μm. If the X-ray source is incoherent and a full-cone condenser with an aperture matched to the X-ray objective is used, the cut-off frequency is extended to 50 LP/μm. However, the contrast transfer rapidly decreases with increasing spatial frequency, as it is common for incoherent imaging systems. The contrast transfer at high spatial frequencies can be increased significantly if the rotating condenser RK20 is employed—however, the contrast transfer at lower spatial frequencies is reduced and at all spatial frequencies (for a given signal-to-noise ratio, e.g. 3, in Fig. 4) the number of required photons is increased significantly.

When the rotating condenser RK70 is employed, the cut-off frequency is reduced to 33 LP/μm. However, the spatial frequency transfer is now linear up to moderate spatial frequencies of about 18 LP/μm; therefore, this imaging condition is superior if quantitative data have to be restored from the images. The estimated image recording times are in the second range according to Fig. 4.

5. Summary

The monochromator–condenser presented here realizes the concept of dynamical aperture synthesis with an off-axis transmission zone plate and a pair of rotating mirrors. The concept is well suited to match the increased brilliance of modern X-ray sources to a TXM, compare also [6].

Acknowledgements

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