Condenser for Koehler-like illumination in transmission x-ray microscopes at undulator sources

Ulrich Vogt and Magnus Lindblom

Biomedical and X-ray Physics, Royal Institute of Technology/Albanova, SE-106 91 Stockholm, Sweden

Pambos Charalambous

Zoneplates.com, 8 South Way, London N9 0AB, UK

Burkhard Kaulich

X-ray Microscopy Section, Sincrotrone Trieste, S.S. 14 in Area Science Park, I-34012 Basovizza-Trieste, Italy

Thomas Wilhein

University of Applied Sciences Koblenz, RheinAhrCampus Remagen, Suedallee 2, D-53424 Remagen, Germany

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We report on a novel condenser for full-field transmission x-ray microscopes that use synchrotron radiation from an undulator source. The condenser produces a Koehler-like homogeneous intensity distribution in the sample plane and eliminates object illumination problems connected with the high degree of spatial coherence in an undulator beam. The optic consists of a large number of small linear diffraction gratings and is therefore relatively easy to manufacture. First imaging experiments with a prototype condenser were successfully performed with the Twinmic x-ray microscope at the Elettra synchrotron facility in Italy. © 2006 Optical Society of America

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Full-field transmission x-ray microscopes (TXMs) are well established instruments at many synchrotron radiation facilities and are applied for investigations in several research areas, e.g., biological cell imaging, defect detection in semiconductor integrated devices, and colloidal science.[1] The basic optical arrangement of a TXM is similar to that of a visible-light microscope and consists of two x-ray optics, a condenser optic for sample illumination, and a high-resolution zone plate objective that forms a magnified image of the sample. First-generation TXMs[2,3] utilized synchrotron radiation emitted from bending magnets. As condensers, large-diameter (millimeters) zone plates were used, which were fitted to the size of the x-ray beam. A condenser forms a strongly demagnified image of the source, and this intensity profile is used to illuminate the sample (critical illumination). A typically illuminated object area (i.e., the image size of the source) is in a range near 20 μm in diameter.

The situation changes if synchrotron radiation from an undulator source has to be employed. In general, the use of an undulator beam line for a TXM is preferable because of the increased x-ray flux, which leads to shorter image acquisition times. However, a conventional condenser zone plate suffers from a high degree of spatial coherence in an undulator beam. Accordingly, the source image formed by the condenser to illuminate the sample will be small and result in an illuminated object area that is too small. Moreover, the coherence will induce strong diffraction patterns from the sample or the zone plate objective that will be superimposed upon the microscopic image. Therefore operation of the microscope without any condenser is also not feasible.

Other condenser systems have been designed to tackle the problems mentioned above. The first one consists of an off-axis zone plate, also acting as monochromator, and a set of rotating mirrors, the so-called rotating condenser.[4] A similar method also uses a moving mirror for coherence control in a microstepper for extreme-ultraviolet lithography.[5] A third approach is the use of a diffractive-optical element that produces a flattoplike intensity profile in the image plane of the microscope.[6] An additional monochromator is needed for this optic.

Here we introduce a novel condenser that is also based on a diffractive optic but has distinct advantages compared with the other two systems. A sketch of the element is shown in Fig. 1. The condenser consists of a number of linear gratings that have ap-

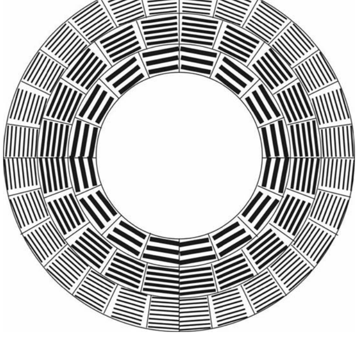

Fig. 1. Design of the condenser, which consists of many small diffraction gratings.

proximately the same size. The orientation of the grating lines of each grating is perpendicular to a connection line between the center of the individual grating and the center of the whole optic. Gratings that have the same distance from the center have the same grating constant, resulting in concentric rings of gratings with equal periods. Each grating causes impinging x rays to be diffracted toward the optical axis, and the grating constants are calculated such that the first diffraction orders overlap on the axis at a certain distance from the optic. Therefore the grating constant decreases with increasing distance from the center. The position where the diffracted light from all gratings overlaps defines the position of the sample plane, and the size of the illuminated area is given roughly by the area of a single grating.

One advantage of this grating condenser is that it does not need the complicated mechanics of a rotating condenser. Although it is similar to that for a flat-topped diffractive-optical-element condenser, the calculation of the grating positions and constants is straightforward, and the fabrication by *e*-beam lithography is much easier. The condenser delivers a Koehler-like homogeneous sample illumination because at each point in the object field a large number of light rays that originate from different parts of the undulator beam coincide, while the number of different rays is simply given by the number of gratings. At the same time, the overlap of the light from different gratings will lead to a strongly decreased degree of spatial coherence in the sample plane. Therefore no diffraction pattern of the sample or the zone plate objective should disturb the image. It has to be noted that an external beam line monochromator delivering moderate monochromaticity is needed for the condenser's operation.

A prototype condenser for use in the Twinmic microscope[7] was designed and fabricated (ZonePlates.com). The condenser has an outer diameter of 1 mm, which fits the undulator beam's size in the microscope. To get a field of view of 50 μm diameter, each grating of the optic has a size of approximately 50 $\mu\text{m} \times 50$ μm, resulting in a total number of 256 grating elements in 5 rings. An inner area of 500 μm diameter is not structured. The grating constants are near 218 nm for the innermost ring and 126 nm for the outermost one. The condenser is made from 115 nm tungsten on a 50 nm thick Si_3N_4 membrane. The basic manufacturing steps are *e*-beam lithography of the condenser pattern in an electron resist and reactive ion etching for the pattern transfer in tungsten.

A ray-tracing simulation that uses the innermost ring of gratings was performed to prove the expected imaging performance of the condenser. The result, depicted in Fig. 2, shows a homogeneously illuminated area of approximately 50 μm (corresponding to the size of a single grating) at the correct distance from the optic on the optical axis.

An experimental test of the condenser was performed with the Twinmic microscope operating in full-field transmission mode.[7] The experimental arrangement is depicted in Fig. 3. The microscope is located at the Elettra synchrotron radiation facility at Trieste, Italy, and temporarily hosted by the Bach beam line (Section 8.1). This undulator beam line features a spherical grating monochromator that can deliver a monochromaticity of $\lambda/\Delta\lambda \geqslant 6000$ sufficient for the operation of the microscope. The light in the monochromator exit slit is imaged by a toroidal mirror and forms a secondary source for the microscope. The condenser was placed approximately 2.5 m from the secondary source, where the beam has a diameter that fits the condenser area. A central stop placed directly after the condenser blocks the direct beam. A 75 μm pinhole in the sample plane filtered out the correct condenser diffraction order. As an objective, a nickel zone plate (KTH Stockholm) with a diameter of 75 μm and an outermost zone width of 50 nm was used. The microscopic image was acquired by an x-ray CCD camera (Roper Scientific) with a pixel size of 20 $\mu\text{m} \times 20$ μm. The undulator gap was set to a wavelength of 1.72 nm, resulting in a working distance of 35 mm for the condenser and a focal length of 2.2 mm for the zone plate.

Three images of a tungsten Siemens star test object are shown in Fig. 4 (exposure time, 10 s). The

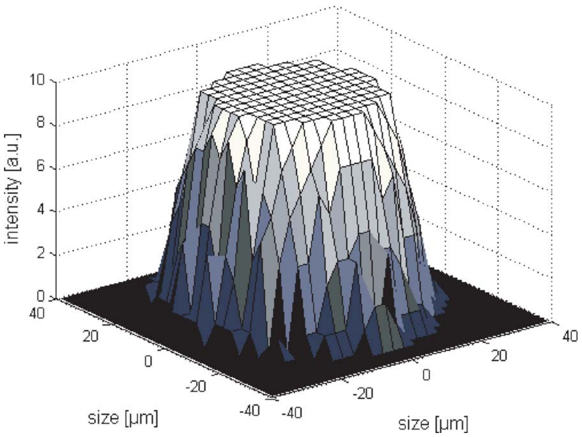

Fig. 2. (Color online) Ray-tracking simulation of the intensity profile in the sample plane produced by the innermost condenser ring. The number of traced rays is 10,000; all rays hitting the condenser are parallel to the optical axis.

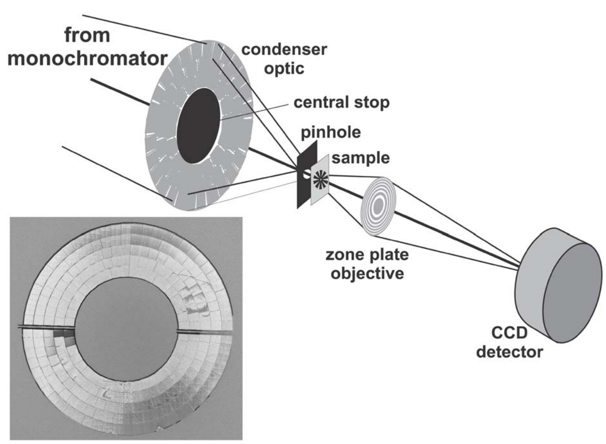

Fig. 3. Experimental arrangement of the Twinmic full-field transmission x-ray microscope. Inset, scanning-electron microscope image of the fabricated condenser.

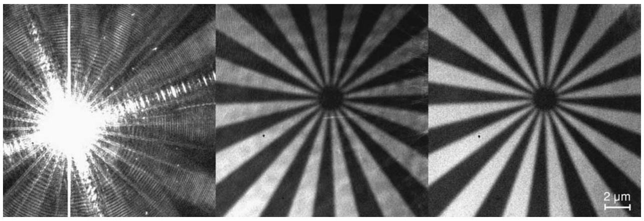

Fig. 4. X-ray microscope images of a Siemens star test pattern (smallest feature size, 400 nm period). Left, image obtained without a condenser; strong diffration artifacts are visible. Center, image with a condenser but with interference artifacts present. Right, image with a condenser and with interference artifacts removed by source vibration. No image processing, but dark image subtraction was performed on the data.

thickness of the star is 100 nm and the period of the inner structures is 400 nm. The microscope was operated with a magnification of 680, resulting in a detector-limited resolution of 50 nm. The leftmost image shows the situation without a condenser. The image of the Siemens star can be seen in the background. However, strong diffraction artifacts from the zone plate as well as from the sample are visible, with an intensity much higher than the microscopic image itself. The large white area in the image is an overexposed area because of the direct x-ray beam's hitting the detector. The center image was made with a condenser. The image quality is significantly improved, but inhomogeneities in the illumination can be seen. These are the result of interference effects of radiation coming from neighboring gratings in the condenser. The interference can easily be canceled out by introduction of a vibration either of the condenser or of the x-ray beam. Note that the amplitude of this vibration has only to be of the order of the largest interference period that is visible in the image, which is as small as $\sim 2\ \mu\text{m}$. For practical reasons, x-ray beam movement was implemented by mechanical vibration of a mirror steering the beam into the microscope's vacuum chamber. The result can be seen at the right in Fig. 4. The interference pattern is smeared out, giving nearly homogeneous illumination.

In summary, we have presented the successful design, fabrication, and testing of a diffractive-optical-element condenser consisting only of linear diffraction gratings. It is especially useful for transmission x-ray microscopes at undulator beam lines. The illuminated area in the sample plane depends on the area of a single grating element and can be adjusted to the needs of the microscope. Furthermore, a Koehler-like illumination is achieved, resulting in a homogeneous intensity distribution and a strongly decreased degree of spatial coherence in the sample plane. Therefore this type of condenser could also be beneficial for microscopes operated with bending magnet radiation or compact laboratory x-ray sources.

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