A microscope for hard x rays based on parabolic compound refractive lenses

B. Lengeler, a) C. G. Schroer, M. Richwin, and J. Tümler
2. Physikalisches Institut, RWTH Aachen, D-52056 Aachen, Germany

M. Drakopoulos, A. Snigirev, and I. Snigireva
European Synchrotron Radiation Facility ESRF, BP220, F-38043 Grenoble, France

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We describe refractive x-ray lenses with a parabolic profile that are genuine imaging devices, similar to glass lenses for visible light. They open considerable possibilities in x-ray microscopy, tomography, microanalysis, and coherent scattering. Based on these lenses a microscope for hard x rays is described, that can operate in the range from 2 to 50 keV, allowing for magnifications up to 50. At present, it is possible to image an area of about 300 μm in diameter with a resolving power of 0.3 μm that can be increased to 0.1 μm. This microscope is especially suited for opaque samples, up to 1 cm in thickness, which do not tolerate sample preparation, like many biological and soil specimens. © 1999 American Institute of Physics. [S0003-6951(99)03726-2]

There is a growing need in basic science and technology for x-ray techniques with a lateral resolution below 1 μm. Besides microdiffraction and microfluorescence, x-ray microscopy in absorption and phase contrast is becoming a more and more important tool in many disciplines, being complementary to other microscopy techniques. The hard x-ray microscopy technique described in this letter requires minimal sample preparation and allows for nondestructive imaging of opaque samples and samples in their natural (e.g., liquid) environment with a resolution of 0.3 μm. While microdiffraction and microfluorescence require devices to generate a small spot, an x-ray microscope calls for high-quality imaging components.

Up to now, curved mirrors and multilayers, single and multiple capillaries, and diffracting lenses have been the standard tools to achieve a small focal spot size. Some of them have been shown to work as imaging devices, with considerable applications in x-ray microscopy and microanalysis. Recently, we have shown that cylindrical and crossed cylindrical x-ray lenses based on refraction can be manufactured giving a focal length in the meter range and a focal spot size in the micrometer range determined by the demagnification of the x-ray source. In the meantime, these lenses have been taken into use by other groups and are installed for beam conditioning in the front ends of some beamlines at the European Synchrotron Radiation Facility (ESRF) in Grenoble. The concept has also been transferred to the focusing of neutron beams. However, these lenses show strong spherical aberration and are not well suited for imaging purposes.

In the present letter, we describe compound refractive lenses (CRL) with a parabolic profile and rotational symmetry around the optical axis. They focus in two dimensions and are genuine imaging devices. They can withstand the full radiation (“white beam”) of an undulator source at the ESRF and might, therefore, be suited to be used together with future free-electron laser sources. The lenses are mechanically robust and easy to align, since they work as in-line devices and do not change the direction of the optical axis. Due to their parabolic shape, they are virtually free of spherical aberration. All that can be done with glass lenses for visible light can also be done with these lenses in the hard x-ray range.

Due to the very weak refraction of hard x rays in matter, a compound refractive lens is composed of many lenses stacked behind each other, as shown in Fig. 1. Its focal length is given by \( f = R/2N\delta \), where \( N \) is the number of individual lenses in the stack, \( R \) the radius of curvature at the apex of the parabola, and \( \delta \) the real-part decrement of the index of refraction \((n = 1 - \delta - i\beta)\). Note that the real part of the refractive index is smaller than one for hard x rays in matter. Therefore, focusing is done by concave lenses.

The lenses described in this letter are made from polycrystalline aluminum by a pressing technique and have been designed and manufactured at the University of Technology in Aachen. The pressing tools consist of two convex paraboloids with rotational symmetry facing each other, guided in a centering ring. The aluminum blank, in which the paraboloids are to be pressed from both sides, is held and centered by a ring that fits tightly into the centering ring, aligning the blank with respect to the paraboloids. The parabolic shape is simultaneously pressed into the aluminum from both sides. Modern computer-controlled tooling machines allow the

\( \text{FIG. 1. Schematic sketch of a parabolic compound refractive lens. The individual lenses (a) are stacked behind each other to form a compound refractive lens (b).} \)
pressing tool to be manufactured with the precision of a micrometer. Positioning the individual lenses behind each other on two high-precision shafts makes it possible to align them with the same precision. The criteria for the material choice have been described in a recent article and details on the lens fabrication will be published.

The most important benefit of these lenses is their ability to image like refractive lenses in classical optics. To demonstrate this, we have used a lens to image an object illuminated by an x-ray beam. The setup used is that for a microscope operating with hard x rays. The object is illuminated from behind by the x-ray source and imaged through the lens onto a position-sensitive detector. As in classical optics, the image is formed at a distance \( L_2 = L_1 f / (L_1 - f) \) behind the lens, where \( L_1 \) is the object-to-lens distance. The magnification is given by the ratio \( m = L_2 / L_1 \), which is large, if \( L_1 \) is chosen slightly larger than the focal length \( f \). Due to the low absorption of hard x rays in air there is no need for a sample chamber. Since the effective aperture of the lens is small (below 500 \( \mu \text{m} \)) as compared to its focal length (~1 m), there is an extended depth of field (~cm), allowing relatively large opaque objects to be imaged.

In the present imaging experiments performed at beamline ID22 of the ESRF, we have used an aluminum parabolic CRL (\( N = 62, R = 0.2 \text{ mm} \), geometric aperture \( 2 R_0 = 0.9 \text{ mm} \), \( f = 1.648 \text{ m} \)) to image several objects onto high-resolution x-ray film using 23.5 keV x rays. For an object-to-lens distance \( L_1 \) of 1.786 m an image (as shown in Fig. 2) is formed at 21.4 m behind the lens. In this particular setup the CRL images an area of about 300 \( \mu \text{m} \) in diameter with a magnification of 12 and a theoretical resolution of \( \Delta_{\text{min}} = 0.34 \mu\text{m} \).

The resolution of the imaging setup is determined both by diffraction at the absorption-limited finite aperture of the lens (\( \mu \) linear attenuation coefficient) and by the surface roughness \( \sigma \) of each of the individual lenses in the CRL. Both effects lead to a blurring of the image that can be accounted for theoretically by diffraction at an effective aperture \( D_{\text{eff}} = 2 R \sqrt{2/(\mu N R + 2 N k^2 \sigma^2 \delta^2)} \), \( (k = 2 \pi / \lambda) \). A point on the object is imaged to an Airy disk, limiting the resolution. If one defines the resolution \( \Delta_{\text{min}} \) of the imaging setup as the distance of two points in the object whose image points are separated by the full width half maximum (FWHM) of the images of each point, one obtains \( \Delta_{\text{min}} = 0.75 L_1 / D_{\text{eff}} \) for incoherent illumination.

Figure 2(a) depicts the x-ray microscopical image of a two-dimensional gold mesh, whose periodicity is 15 \( \mu\text{m} \) in both directions. The image of the mesh shows almost no distortions over a field of view of about 300 \( \mu\text{m} \). The image intensity decreases towards the outside, due to increased attenuation in the outer parts of the lens. Inhomogeneities in the primary beam visible here could be removed by subtracting a flat-field image. [The fuzziness in the parts with high intensity in Fig. 2(a) is due to the limited dynamic range of the camera used to digitize the image recorded on the x-ray film.] In Fig. 2(b) an enlargement of the region inside the rectangle in Fig. 2(a) is shown. A grid of horizontal gold wires (0.5 \( \mu\text{m} \) width, 1 \( \mu\text{m} \) periodicity) arranged behind the lower part of the coarse Au mesh is clearly resolved. Note that the wires are also visible behind the gold bars of the mesh, illustrating the imaging possibilities of opaque samples. In order to quantify the lateral resolution \( \Delta_{\text{min}} \) of our microscopical setup we have measured the image of a knife edge. For that purpose a broken InAs wafer with a sharp edge was imaged with 25 keV photons and an Al CRL with \( N = 100, f = 1.085 \text{ m} \) (Fig. 3). The wafer absorbs the x rays almost completely in one half of the illuminated area. It generates a transition range in the intensity at \( x = 0 \) with a width \( \Delta_{\text{min}} \) of 0.34 \( \mu\text{m} \). The theoretical resolution of this particular setup is 0.24 \( \mu\text{m} \). This underlines the quality of the CRL described in the letter.

As the effective aperture \( D_{\text{eff}} \) is mostly limited by absorption in the lens material, choosing a more transparent material such as Be or B can improve the resolution of the setup. Using, for example, a Be CRL, a resolution of 0.1 \( \mu\text{m} \) should be possible.
is feasible. This is an interesting perspective for nondestructive microscopy of opaque objects with hard x rays.

In microanalysis and coherent scattering a small spot size and high intensity are needed on the sample. This is achieved by imaging the source onto the sample in a strongly demagnifying setup. The gain of a given setup, defined as the ratio of the intensity in the focal spot divided by the intensity in a pinhole of equal size, is typically of the order 100 for aluminum lenses.

To demonstrate this, a compound refractive lens was used to image the undulator source of ID22 onto a position-sensitive detector. At 15 keV, an aluminum CRL \([N = 33, f = 1.257 \text{ m}, d = 20 \mu \text{m} \text{ (cf. Fig. 1)}] \) was placed into the beam at a distance \(L_1 = 63 \text{ m} \) away from the source. In this setup the image of the source is formed in the detector at \(L_2 = 1.283 \text{ m} \) behind the lens. During this experiment the effective source size (FWHM) of the high \( \beta \) undulator, as seen from the lens position, was \(b_v = 35 \mu \text{m} \) in the vertical and \(b_h = 700 \mu \text{m} \) in the horizontal with an uncertainty of the order of 10%. Figure 4 shows the recorded image of the source, which in this setup is demagnified by a factor of 49. The measured focal spot sizes in horizontal and vertical directions are 14.0 and 1.6 \( \mu \text{m} \) FWHM, respectively. The geometrically demagnified source size, 14.2 \( \mu \text{m} \) (horizontally) by 0.71 \( \mu \text{m} \) (vertically), is broadened by diffraction and surface roughness to 14.3 \( \mu \text{m} \) by 0.98 \( \mu \text{m} \). Further broadening due to the detector point spread function (1.2 \( \mu \text{m} \) FWHM) yields a theoretical image size on the detector of 14.3 \( \mu \text{m} \) by

1.58 \( \mu \text{m} \), in good agreement with the experimental results. The measured gain in this setup is 177.

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FIG. 4. Image of the undulator source at beamline ID22 of the ESRF as imaged by an Al CRL at 15 keV.