Coherence-matched microfocusing of hard x rays

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(Received 8 November 2004; accepted 3 March 2005; published online 12 April 2005)

An efficient, high-resolution microfocusing device for hard x rays is presented. A combination of two linear zone plates mounted with orthogonal orientation is used to provide two-dimensional focusing. Choosing appropriate lens parameters, the device can be matched to the quasielliptical shape of most synchrotron x-ray sources to obtain a symmetric, circular-shaped focal spot. A rectangular device aperture allows the maximization of the light-collecting area and to simultaneously achieve a highly coherent illumination of the device. Such a setup was tested at the European Synchrotron Radiation Facility and test gratings with minimal line widths of 140 nm could be resolved. The gain in flux density was found to be 10^5 for 12.7 keV photons. © 2005 American Institute of Physics. [DOI: 10.1063/1.1905782]

X-ray diffractive lenses (zone plates) are widely used as imaging and focusing devices at synchrotrons. One important application of zone plates is microfocusing of x rays, where the light stemming from a source is imaged into a small focal spot. By scanning the resulting spot across a sample it is then possible to obtain spatially resolved information about the investigated object, using a large variety of x-ray techniques, e.g., diffraction, scattering, spectroscopy, and fluorescence analysis. For all lenses the achievable size of the microfocus, and therefore the resolution of the microfocusing device, is limited by the inevitable diffraction at the lens aperture. For zone plates the resolution limit is found to be approximately equal to the minimal outermost zone width $\Delta_{\min}$ at the edges of the lens.¹ Zone plates with minimal zone widths down to about 20 nm have been fabricated,^{2–4} and these devices achieve the highest resolution of all types of x-ray lenses. Such narrow zone structures cannot be made much higher than a few hundred nanometers. Therefore, these high resolution lenses give good diffraction efficiency of about 10% only for soft x rays ($h\nu < 1$ keV). For hard x rays with photon energies above 10 keV similar efficiencies require structure heights of typically several microns. This is the reason why no hard x-ray zone plates are available that provide submicron resolution and, at the same time, have a high efficiency.

One essential precondition to obtain a resolution close to the diffraction limit δ is a spatially coherent illumination of the zone plate. The transverse coherence lengths in vertical (L_v) and horizontal (L_h) direction define the size of the according coherently illuminated area (see Fig. 1), with $L_{v,h} = \lambda p / s_{v,h}$, where $s_{v,h}$ is the source size in vertical/horizontal direction, p the distance to the source, and λ is the x-ray wavelength.⁵ If the lens aperture is larger than the transverse coherence lengths, one finds that the vertical and the horizontal size of the geometrical image of the x-ray source (g_v and g_h) become of the same order or larger than the diffraction limited spot size δ . Consequently the size of the resulting microfocus will be further increased due to the non-negligible extension of the x-ray source. In praxis one

therefore often chooses a lens diameter that is approximately equal to the transverse coherence length as this allows for a resolution close to the diffraction limit and at the same time to collect a large area of the incoming x-ray beam.

For most synchrotron beam lines the horizontal source size s_h is significantly larger than the vertical source size s_v . This asymmetry $a = s_h/s_v$ is typically in the order of 5–10 and results in strongly different coherence lengths in vertical and horizontal direction given by $a = L_v/L_h$ (see also Fig. 1). Consequently, a round zone plate with a certain diameter D is not well suited to collect the light within the resulting coherently illuminated area. For coherent illumination in both directions ($D \leq L_h$) a large fraction of the incoming coherent photons is lost. Choosing $D \approx L_v$ would lead to a strongly incoherent illumination in horizontal direction and result in a horizontal spot size that is significantly larger than the diffraction limited spot size δ . In fact one finds that the obtained focal spot will always be asymmetric unless the lens diameter is chosen much smaller than the coherence lengths in both directions. Both problems, the bad match of a round zone plate to the coherently illuminated area as well as the resulting asymmetric focal spot can be avoided using two crossed linear zone plates arranged as shown in Fig. 1. Each linear zone plate acts as cylindrical lens, enabling an independent focusing in vertical and horizontal direction. Within

FIG. 1. Microfocusing device consisting of two crossed linear zone plates. Using appropriate lens parameters the device can be matched to the asymmetry of a specific x-ray source. In comparison to a conventional round zone plate this results in an increased flux in the focus and enables a symmetric micro-focus. The lenses are tilted with respect to the x-ray beam to optimize their diffraction efficiency.

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FIG. 2. Linear zone plate with 1.5 μm high silicon structures and 100 nm outermost zone width, fabricated by anisotropic wet etching.

certain practical limits the focal lengths and diameters can be chosen freely. Choosing $D_v/D_h=a$ as well as $f_v/f_h=a$ compensates for the asymmetry of the source and, as shown later, results in a symmetric focal spot. Contrary to a round zone plate it is possible to simultaneously match the lens diameters to the transverse coherence lengths by choosing $D_v \approx L_v$ and $D_h \approx L_h$, making it possible to cover the whole coherently illuminated area and at the same time to achieve a resolution close to the diffraction limit.

Applying this approach of a coherence-matched micro-focusing, a setup consisting of two linear silicon zone plates was built at the microfocus beamline ID13 of the European Synchrotron Radiation Facility. The silicon zone plates were fabricated with a process described in detail elsewhere,⁶ using electron-beam lithography and anisotropic wet etching of silicon. The high anisotropy of the wet-etch process allowed for the fabrication of zone plate grating structures with high aspect ratios, with minimal zone widths $\Delta_{\min}$ of 100 nm for a structure height of 1.5 μm (see Fig. 2). By tilting the zone plate with respect to the x-ray beam the effective grating structure height was further increased⁷ (see also Fig. 1) and tuned to the optimal structure height for maximal diffraction efficiencies. The undulator at ID13 has an x-ray source size of about $140 \mu\text{m} \times 25 \mu\text{m}$. The focusing device was placed at 35 m distance from the source. Using a silicon (111) double monochromator a photon energy of 12.7 keV was chosen for the experiment, resulting in transverse coherence lengths of $L_h=25 \mu\text{m}$ and $L_v=140 \mu\text{m}$. In order to collect a large fraction of the incoming beam it was decided to accept a relatively incoherent illumination of the focusing device and also a slight asymmetry of the focal spot. Consequently, lens diameters of 50 μm and 200 μm were chosen in vertical and horizontal direction, respectively. Both zone plates had a minimal outermost zone width of 100 nm, resulting in focal lengths of $f_h=51 \text{ mm}$ and $f_v=204 \text{ mm}$ for the chosen photon energy.

To test the resolution of the focusing device a gold test grating with continuously varying grating period was scanned through the focal spot formed by the two crossed linear zone plates. Due to the absorption of the gold grating a variation of the transmitted x-ray beam between a maximal value $S_{\max}$ and a minimal value $S_{\min}$ is observed. Measuring the visibility V defined as $V=(S_{\max}-S_{\min})/(S_{\max}+S_{\min})$ for different grating periods and for horizontally and vertically orientated gold test gratings, the modulation transfer function of the focusing device is obtained (see Fig. 3). For the horizontal as well as for the vertical direction a cut of frequency of about $3.5 \mu\text{m}^{-1}$ is found, meaning that the focusing device can resolve gratings with grating lines and spaces down to 140 nm.

FIG. 3. Modulation transfer functions obtained by taking horizontal and vertical scans across a gold test grating. The right ordinate shows the visibility normalized with respect to V_0 , where V_0 is the visibility for infinitely large grating periods. V_0 was obtained by calculating the transmission of a gold layer for the given layer thickness of 350 nm. The transmission for the vertical scan is shown in the inset.

For the lenses used within the setup, an efficiency of $\eta = 26\%$ was measured, resulting in a total focusing efficiency η_c of the device of about 7% ($\eta_c = \eta^2$). Obviously, using two linear zone plates in series has the disadvantage that losses in two optical components have to be considered. However, for a single, conventional round zone plate neither the wet-etch fabrication process nor the tilting technique, which enable extreme aspect ratios up to 200 for linear grating structures, can be applied. As a consequence, the fabrication of round zone plates for the hard x-ray range above 10 keV, having a comparable resolution and total efficiency, is extremely difficult and has not been demonstrated up to now. In addition the device consisting of two crossed linear lenses can be matched to the asymmetric shape of synchrotron x-ray sources. This results in a better performance in terms of focal spot shape, spot size and flux within the spot.

For a thorough comparison of a round zone plate and two crossed linear zone plates one needs to calculate the intensity distribution within a focus for different sizes of the according lens apertures. One useful set of parameters for characterizing the resulting focal spots are the full width at half maximum (FWHM)-spot sizes w_h and w_v in horizontal and vertical direction. For a simple analytical calculation of w_h and w_v one can assume Gaussians for the shape of the diffraction limited spot as well as for the geometrical image of the source. The error is found to be in the order of only a few percent. Within this approximation the focal spot, which represents a convolution between the diffraction limited spot and the geometrical source image, is also a Gaussian with

$$w_{v,h} = \sqrt{g_{v,h}^2 + \delta^2}. \quad (1)$$

The distance to the x-ray source is normally very large compared to the focal lengths, so that the size of the geometrical source image is calculated as $g_{v,h} = s(f_{v,h}/p)$. The diffraction limited FWHM-spot size δ is determined by the numerical aperture and the x-ray wavelength via $\delta = k\lambda/(2NA)$, where NA is given by the diffraction angle at the border of the zone plate $NA = D/(2f) = \lambda/(2\Delta_{\min})$. The value of the dimensionless factor k depends on the aperture of the focusing device and is found to be 1.02(k_r) for a round zone plate and 0.90(k_c) using two crossed linear zone plates, which together

FIG. 4. Calculated focal spot widths obtained using a round zone plate and a coherence-matched device consisting of two crossed linear zone plates. A source asymmetry $a=5.6$ as in the experiment is assumed for the calculations. The spot widths are shown as a function of the aperture areas, which are normalized with respect to the size of the coherently illuminated area given by $L_v L_h$.

form a rectangular aperture. Rearranging Eq. (1) we obtain a formula for the spot widths depending on the outermost zone width $\Delta_{\min}$ and on the relative size of the lens-apertures compared to the transverse coherence lengths

$$W_{v,h} = \Delta_{\min} \sqrt{(D_{v,h}/L_{v,h})^2 + k^2}. \quad (2)$$

From Eq. (2) it follows that decreasing the outermost zone width $\Delta_{\min}$ makes it possible to achieve smaller spot widths or to use larger light-collecting apertures (while keeping the spot width constant). Consequently, one generally chooses a zone width equal to the minimal achievable zone width Δ_{fab} for a given fabrication process. If two linear lenses have the same outermost zone width (with $\Delta_{\min} \approx \Delta_{\text{fab}}$) they also have the same numerical aperture leading to $D_v/D_h = f_v/f_h$. Considering Eq. (1) one then finds that for a device with $D_v/D_h = a$ it is possible to obtain a symmetric focal spot, having the same width in horizontal and vertical direction ($w_v = w_h$). For this special choice the relative size of the lens diameters compared to the transverse coherence lengths is the same in vertical and horizontal direction ($D_v/L_v = D_h/L_h$). Such a coherence matching allows to minimize the broadening of the focal spot resulting from incoherent illumination. Quantitatively one can show that choosing $D_v/D_h = a$ results in a minimal focal spot area defined by $w_h w_v$ comparing crossed linear zone plates which have the same outermost zone widths and achieve the same light collecting area but use different ratios of D_v/D_h .

For a direct comparison of a round zone plate and a coherence matched device consisting of two linear zone plates it is useful to express Eq. (2) as a function of the normalized aperture area $A_{\text{norm}} = A/(L_h L_v)$, where A is the light collecting area of a device. Figure 4 shows a plot of the resulting focal spot widths, which are normalized with respect to the outermost zone width $\Delta_{\min}$. For the comparison it is reasonable to assume the same outermost zone width for both devices, as a fabrication process suitable for round zone plates is also applicable for linear zone plates. For large apertures ($A_{\text{norm}} \gg 1$, incoherent illumination) the spot widths are found to be considerably larger than the diffraction limit δ (with $\delta \approx \Delta_{\min}$) for both types of devices. Using two

crossed linear lenses for the case of almost coherent illumination ($A_{\text{norm}} \approx 1$, and therefore $D_v \approx L_v$ and $D_h \approx L_h$) allows for both, to collect a comparatively large fraction of the incoming beam and to achieve a resolution that is already close to the diffraction limit. The competing round zone plate of the same aperture area ($A_{\text{norm}} \approx 1$) shows a similar resolution in vertical but a much worse resolution in horizontal direction. To a certain extent the better performance of two crossed linear lenses results from the fact that they achieve a slightly smaller diffraction limited spot than a round zone plate. However, for large asymmetries a of the x-ray source (as in Fig. 4 with $a=5.6$) the better resolution mainly results from fact that two crossed zone plates allow to achieve a rectangular, coherence matched device aperture.

One possibility to quantify how much one gains using two crossed zone plates instead of a round zone plate is to compare devices that achieve the same area of the focal spot (defined by $w_h w_v$). Considering the experimentally tested focusing device as an example, the spot widths in horizontal and vertical direction are calculated as $w_h = 220$ nm and $w_v = 170$ nm. The corresponding round zone plate, achieving the same focal spot area, is found to have a diameter D of $76 \mu\text{m}$, leading to a focal spot of $w_h = 320$ nm and $w_v = 120$ nm. Consequently, the round zone plate has a factor 2.2 smaller light collecting area and has the disadvantage that it yields a considerably asymmetric focal spot.

Taking into account the experimentally determined total efficiency η_c of the device and the theoretical focal spot sizes w_h and w_v , it is possible to calculate the gain G_I in intensity in comparison to a situation without any focusing device, leading to $G_I \approx 10^5$.

The results show that a combination of two crossed linear zone plates forms a versatile and efficient tool to achieve a very small and symmetric microfocus of hard x rays above 10 keV. A total efficiency of about 7% and a resolution of 140 nm were demonstrated. The theoretical limit for two zone plates with binary structures is $(40.5\%)^2 = 16\%$. A possibility to increase this value is to use zone plates with multilevel structures, which have been demonstrated to yield lens efficiencies up to 65%.⁸

The authors wish to thank Bianca Haas, Andreas Grubelnik, and Roland Widmer for their technical support in fabricating the linear zone plates. This work was partially funded by the Swiss National Science Foundation.

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