X-ray focusing with compound lenses made from beryllium

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We have measured the intensity profile and transmission of x rays focused by a series of biconcave spherical unit lenses fabricated from beryllium. The use of beryllium extends the range of operation of compound refractive lenses, improving transmission, aperture size, and gain. The compound refractive lens was composed of 160 biconcave unit lenses, each with a radius of curvature of 1.9 mm. Two-dimensional focusing with a gain of 1.5 was obtained at 6.5 keV with a focal length of 93 cm. The effective aperture of the compound refractive lens was measured as 600 µm, with 9% peak transmission. © 2002 Optical Society of America

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A series of N lenses can be used to achieve one- and two-dimensional focusing and imaging of x-ray photon energies.\textsuperscript{1–13} In this Letter a large-aperture compound refractive lens (CRL) composed of 160 separate biconcave spherical lenses, each made from Be, was fabricated and tested, demonstrating a 93-cm focal length at 6.5 keV.

It is known that for visible optics\textsuperscript{14} the focal length of a series of N lenses in contact with one another is reduced by 1/N. Thus, as shown in Fig. 1, x-ray CRLs with short focal lengths have been made by use of a linear array of N closely packed biconcave lenses with radius of curvature R made from low-atomic-number (Z) materials. The focal length is given by

\[ f = \frac{R}{2N\delta}, \]

where the complex refractive index of the CRL material is expressed by

\[ n = 1 - \delta - i\beta. \]

For a biconcave parabolic lens the total thickness of the material in the compound system increases as the square of the distance from the lens axis, and the rays experience increased attenuation with increasing radius. Thus, the CRL acts as an iris as well as a lens. The attenuation radius, \( r_a \), is defined as the value of the radial coordinate where there is an e\textsuperscript{-2} attenuation of the x-ray power through the CRL system. It is expressed as a function of the focal length, \( f \), as\textsuperscript{9,10}

\[ r_a = (4\delta f / \mu)^{1/2}, \]

where \( \mu \) is the linear attenuation coefficient of the lens material. Equation (3) implies that the aperture is determined solely by the focal length and the choice of lens material. The same is true for resolution and depth of focus, which are also a function of aperture.\textsuperscript{9–12} Figure 2 shows aperture diameter as a function of photon energy for selected low-Z materials for CRLs of 1-m focal lengths, where \( D_a = 2r_a \). This value establishes that CRLs made with Be and Li unit lenses achieve larger apertures than CRLs assembled with unit lenses formed from other materials.

If attenuation is neglected, only the central part of a spherical lens approximates the parabolic shape of lenses with no spherical aberration. Parabolic aperture radius \( r_p \) is\textsuperscript{5}

\[ r_p = (4R^2\lambda r_p)^{1/4} \approx \left( \frac{2R^2\lambda}{\delta N} \right)^{1/4}. \]

Here \( r_i \) is the image distance and \( \lambda \) is the x-ray wavelength. Rays outside this aperture do not focus at the same point as those inside. The approximation in Eq. (4) follows from the lens equation \( 1/r_o + 1/r_i = 1/f \) when the object distance \( r_o \gg f \).

An application of CRLs is to increase the image intensity of a distant source (e.g., a synchrotron). The gain is defined as the ratio of the intensity at the CRL’s image plane to the intensity at the same plane without the CRL. The gain on axis of a two-dimensional lens is found from diffraction theory to be\textsuperscript{5}

\[ G = \exp(-\mu Nd) \approx \left( \frac{A_t}{A_s} \right) M^2 T, \]

Here \( k \) is the photon wave number, \( \sigma_h \) and \( \sigma_v \) are the dimensions of the source in the horizontal and vertical directions, respectively, and \( T \) is the average transmission through the lens. The source size area is given by \( A_s \), and the demagnification is \( M = r_n/f \). For unit lenses with aperture radii approximately equal to the attenuation aperture radii \( r_a \), the average

Fig. 1. Series of unit lenses that form a CRL to reduce the overall focal length.
transmission is $T = 0.43 \exp(-\mu Nd)$, where $d$ is the minimum thickness of the unit lens. The effective aperture area of the lens, $A_e$, is the minimum of either the parabolic or the attenuation aperture area; in this case the areas are both approximately equal to 0.3 mm$^2$ at 6.5 keV.

As can be seen from Eq. (5), there is a strong dependence of the gain on the choice of lens material by means of the real part of refractive index $\delta$ and linear attenuation $\mu$ at a given energy. However, the gain is determined by the parameters of both the source and the CRL rather than simply by the material of the CRL. Thus the gain is not a particularly good property with which to compare CRLs that do not share equivalent source areas $A_s$ and distances $r_o$. Depending on the application, the transmission, focal length, and aperture size of the CRL might be better parameters for comparing lenses. The unit lenses that we manufactured were biconcave and spherical with radii of curvature $R = 1.9$ mm. Each Be unit lens had a maximum thickness of 0.76 mm and a minimum thickness $d = 40 \, \mu m$, with a mechanical aperture $2r_m = 2.29$ mm (Fig. 1). The lenses were first machined and then compressed by use of techniques detailed in Ref. 13.

Experimental measurements were performed at the bending magnet beam line 2-3 at the Stanford Synchrotron Radiation Laboratory (SSRL). This beam line possessed a double-crystal monochromator that was capable of delivering x rays from 2400 to 30,000 eV with $5 \times 10^{-4}$ resolution. The nominally expected source size (FWHM) at the SSRL beamline 2–3 is $0.44 \, \text{mm} \times 1.7 \, \text{mm}$.25 However, the actual source size is uncertain because it was not measured at the time of the experiments. The experimental apparatus is shown in Fig. 3 and is the same as that specified in Refs. 8–13. The x-ray beam size was reduced to approximately $1.0 \, \text{mm} \times 1.0 \, \text{mm}$ by Ta entrance slits (horizontal and vertical slits) upstream of the CRL.

The Be CRL was placed 16.8 m from the source in a goniometer head (not shown in Fig. 3), which could be manually tilted in two axes. The lens could also be translated orthogonally (x or y) to the direction of the x-ray beam. These adjustments maximize the x-ray transmission through the lens by aligning it with the beam.

An x-ray detector (ionization chamber) with a Ta exit slit was used to profile the x-ray beam. The exit slit’s dimension was adjusted to below $25 \, \mu m$ by use of a thin, stainless-steel shim. It is likely the exit slit’s jaws were not ideally parallel at these small dimensions. Consequently, the exit slit width was minimally $>3 \, \mu m$ when its jaws appeared to be entirely closed. After its width was adjusted, the exit slit was translated in the x and y directions across the focused x-ray beam. The ionization chamber was at a fixed position downstream from the exit slit so that it measured the total x-ray power passing through it.

The profiles of the x-ray beam along the propagation direction were obtained by placement of the exit slit at different positions along the z axis of the x-ray beam. We measured the vertical and horizontal widths by scanning the horizontal and vertical exit slits, respectively, over the beam at each location on the z axis. The profile of the beam size as a function of distance from the lens was plotted with these measured widths. Figure 4 shows a series of vertical spot sizes of 6.5-keV photons as a function of distance along the propagation direction from the Be CRL. The minimum waist of 42 $\mu m$ can be seen to be at the image distance, $r_i$, of 93 cm downstream from the lens. The measured image spot profile is displayed in Fig. 5. The measured FWHM spot size of the image, 42 $\mu m$, is approximately twice as large as would be expected from the geometric-optics demagnification calculation of 20 $\mu m$. The large image spot diameter can be attributed primarily to surface irregularities or the uncertainty of the source size.

![Fig. 2. CRL attenuation apertures as a function of photon energy for lenses with focal length of 1 m made from Li, Be, Kapton (polyimide film), C, and Al. The figure establishes that x-ray CRLs assembled with Be unit lenses have approximately a factor-of-2 larger apertures at the softer x-ray energy range of the figure (roughly less than 15 keV).](Image 74x608 to 274x741)

![Fig. 3. Experimental setup for testing the prototype Be CRL.](Image 319x262 to 554x324)

![Fig. 4. Measured vertical profiles of 6.5-keV x rays focusing along the propagation direction. The minimum spot 42-$\mu$m-wide FWHM was found at ~93 cm from the lens.](Image 335x87 to 539x224)
The large source size of the SSRL beam implies the theoretical gain is 6, assuming a source size as given in Eq. (3). 2r_α, is calculated to be 607 μm. This value coincides with the measured attenuation aperture width of 600 μm displayed in Fig. 6. The peak transmission of the lens, i.e., transmission on the lens axis, was found to be 9% at 6.5 keV. Decreasing the wall thickness, d, from 40 to 20 μm (achievable with present machine shop practices) can further increase the transmission and the gain.

Given the measured transmissions and profiles one can determine the gain of a CRL from Eq. (5). The calculated experimental gain is 1.5 and the theoretical gain is 6, assuming a source size as given by SSRL. The large source size of the SSRL beam line 2-3 limits the expected gain. If the same Be CRL is placed on a beam line by use of a third-generation x-ray source, the CRL gain can be substantial because of the smaller source sizes and longer source-to-lens distance of these advanced sources.

In conclusion, it has been shown that a CRL made from Be can achieve submeter focal lengths at lower x-ray energies (~6.5 keV) than for previously reported CRLs and still have what are believed to be the largest reported apertures (~600 μm). Thus, it is expected that Be CRLs can outperform lenses constructed of higher-atomic-number materials at energies below 30 keV. The use of the CRLs at these x-ray energies can have wide application in synchrotrons, novel x-ray sources, medical imaging, and microscopy.

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