Fabrication and Evaluation of Variable Focus X-ray Lenses

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We report on the fabrication and preliminary metrology and X-ray transmission results of *variable focus* cylindrical beryllium lenses. Each lens consists of a number of 1-mm-diameter lenslets made by precision computer numerical control (CNC) drilling into a beryllium substrate. The substrate is then cut into five parts each having a different number of lenslets, ranging from 10 to 50. Each lens is then cut diagonally, using an electron discharge machine, to provide it with focusing ability. Unlike the traditional lenses having a fixed focal distance for a given energy, the present lenses provide for a wide range of photon energies and focal distances. Additional, X-ray transmission through the lens is enhanced by reducing lenslet wall thickness to about 50 µm, the thinnest reported to date.

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1. Introduction

Micro- and nanometer-sized X-ray beams are in increasing demand for a wide range of applications. They can be produced by focusing X-ray beams (from synchrotron or lab-based X-ray sources) using a variety of techniques. By virtue of their small sizes, expected to go to as low as 1 nm in the near future, such focused beams provide a means to study specimens with a higher degree of spatial resolution and sensitivity.

X-rays can be focused by a range of optics, including mirrors, crystals, capillaries, waveguides, zone plates and refractive lenses. The choice of the technique used depends on the desired focused beam size, energy, bandwidth, intensity, and other experimental imperatives. X-ray lenses were first proposed by Tomie in 1994 [1] and realized by Snigirev in 1996 [2]. The theoretical basis for their performance was developed earlier [3]. Lenses are cost effective, they have simple designs, are and relatively insensitive to figure and finish imperfections, and are easy to install and use (usually mounted on a motorized stage in air). A typical lens is composed of a number of concave lenslets in series each of which contributes modestly to focusing. The focal distance f for an X-ray lens is given in the thin lens approximation by:

$$f = \frac{R}{2N\delta}, \tag{1}$$

where R is the lenslet radius, N is the number of lenslets (typically 10-100), and δ is the real index of refraction decrement. To a first approximation (ignoring the diffraction limit), the width of the focal spot is obtained by dividing the source width by the demagnification factor, while the gain (in one-directional focusing) is the product of the demagnification factor and the lens transmission (accounting for absorption in the lenslet walls).

To reduce absorption of X-rays in lenses, low atomic number materials such as Li, Be, Al, Si, PMMA, Mylar, and Ni are most often used [4-19]. In fact, for best performance, the ratio δ/β, where β is the material absorption coefficient should be as large as possible for the X-ray energies of interest. Of all room-temperature solids, LiH is the best, followed by Li, and Be. Beryllium is highly merchantable and can be polished if needed, but because of its safety issues fabrication and machining must be carried out by trained personnel in a proper environment.

We have fabricated two generation of beryllium X-ray lenses before [4,5], and here we report on a new generation of Be lenses that have variable-focus [6]. Unlike the traditional lenses with a fixed focal distance for a given energy, this design permits a single lens to be used for a wide range of energies and desired focal distances. The design and fabrication of such a lens is briefly described here together with some preliminary metrology and X-ray transmission results.

2. Beryllium Lenses

Beryllium lenses were fabricated by precision drilling of holes, 1 mm diameter and 10 mm deep, into a 20-mm-thick beryllium substrate. The beryllium used as the substrate is S-200F, which has relatively high purity except for BeO which can be as high as 1.5%. A total of about 150 lenslets were drilled into a single block, which was subsequently cut to produce lenses with 10, 20, 30, 40, and 50 lenslets. Each lens was then cut diagonally such that the depths of the lenslets vary from 10 to 2 mm from end-to-end, as shown in Fig. 1. In practice, to collimate or focus an X-ray beam in the horizontal direction, for example, the lens is moved up and down (along the Z-axis in Fig. 1) to allow the beam to go through more or fewer lenslets to achieve the desired focal distance. Multiple lenses can be aligned in series, if necessary, to provide a wider range of focal lengths.

The fabrication surface roughness specified was 0.4 µm rms. An axial line scan along a typical lens using a Dektak stylus profiler is shown in Fig. 2 indicating an rms wall roughness of about 0.5 µm, while the maximum peak-to-valley surface height is 2.8 µm.

3. X-ray Measurements

A preliminary experiment to determine the transmission of X-ray through the lens having 50 lenslets was carried out at the beamline 7-ID at the Advanced Photon Source. The beamline monochromator is 30 m from the source and set to diffract 11.0 keV X-rays. An aperture to reduce the beam size was placed 220 mm upstream of the lens center. The vertical opening was set to 50 microns, and the horizontal size was set at 20 microns. Two ion chambers were used to record the X-ray signals upstream and downstream of the lens. A series of measurements were carried out to measure the attenuation coefficient and a transmission map of the X-ray beam through the lens. The theoretical linear attenuation coefficient, μ_l, of beryllium is $\mu_l = (4\pi/\lambda)\beta = 0.123\text{mm}^{-1}$ where λ is the radiation wavelength (1.127 Å @11 keV) and β is the imaginary part of the refractive index of beryllium. A direct comparison of the incident beam intensity and the transmitted intensity through the thickest part of the lens (52.5 mm of Be) yielded an absorption coefficient of 0.134 mm^{-1} which is in good agreement with a previous value obtained at this beamline [6], and compares well with the calculated value above. The lens transmission profile shown in Fig. 3 shows a linear cut through the transmission data. It shows the transmission of X-rays as the lens is translated through the beam from one (on the left) to 50 lenslets in the beam. An exponential fit to the attenuation profile is indicated with a dashed line, which shows an average attenuation coefficient of approximately 0.05 mm^{-1}, which when corrected for attenuation in air, indicates the

absorption coefficient of Be is slightly less than 0.13 mm^{-1}. The disparity between this value and the earlier quoted value could be attributed to the presence of higher harmonics of the undulator spectrum in the beam, which were not removed by detuning the monochromator for this measurement.

5. Conclusions

The design of a new generation of Be lenses that provide continuously variable focal distance for a wide X-ray energy range is described. Through CNC machining and with minor post-machining operation, a surface roughness of about 0.5 µm rms with a record 50 µm lenslet wall thickness were achieved. Preliminary X-ray measurements indicate that the Be grade used does not have significant impurity, and can be machined with thin walls of a few grains. Our plan is to continue evaluation of these lenses, and proceed to the next generation of lenses to advance the fabrication processes with the goals of reducing wall roughness and thickness. In addition, we will carry out wavefield calculations to simulate the lens performance by including surface imperfections in the analysis for an understanding of their impact on lens performance.

6. Acknowledgements

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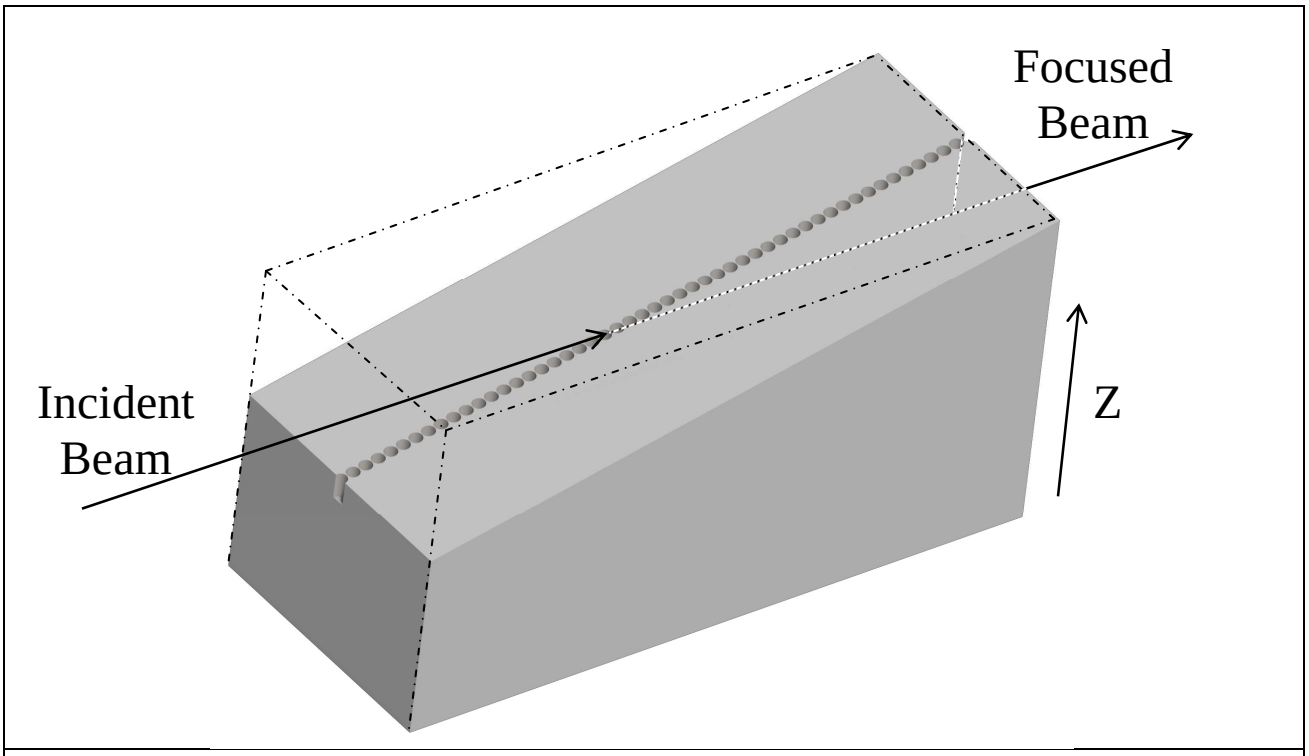

Figure 1: A variable-focus beryllium X-ray lens of 50 lenslets with a substrate envelope size of 52.5 mm x 10 mm x 10 mm. Focal distance is selected through vertical translation of the lens along Z direction.

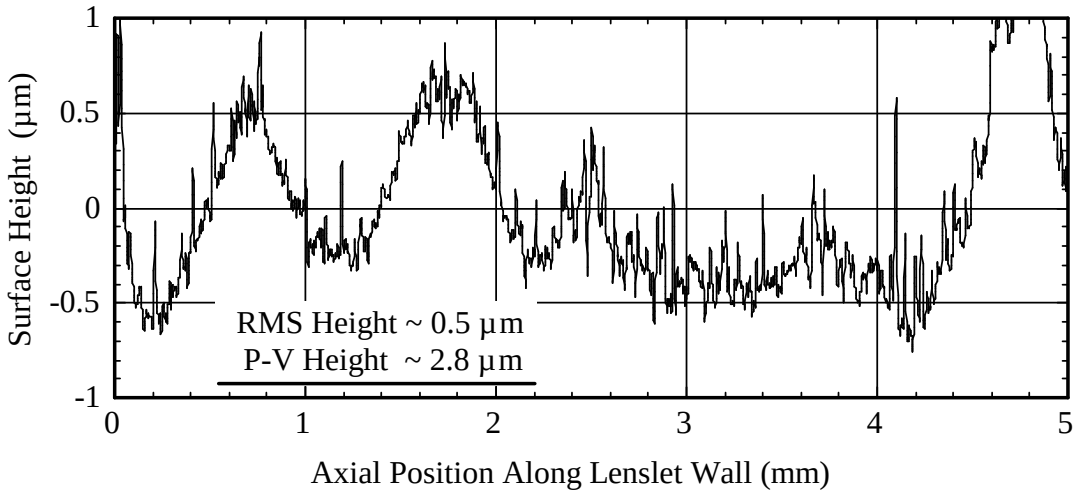

Figure 2: Lens surface "roughness" as determined by a stylus profiler (Dektak) along a 5-mm axial line along a lenslet wall. The rms roughness is 0.5 µm, slightly above the 0.4 µm specified.

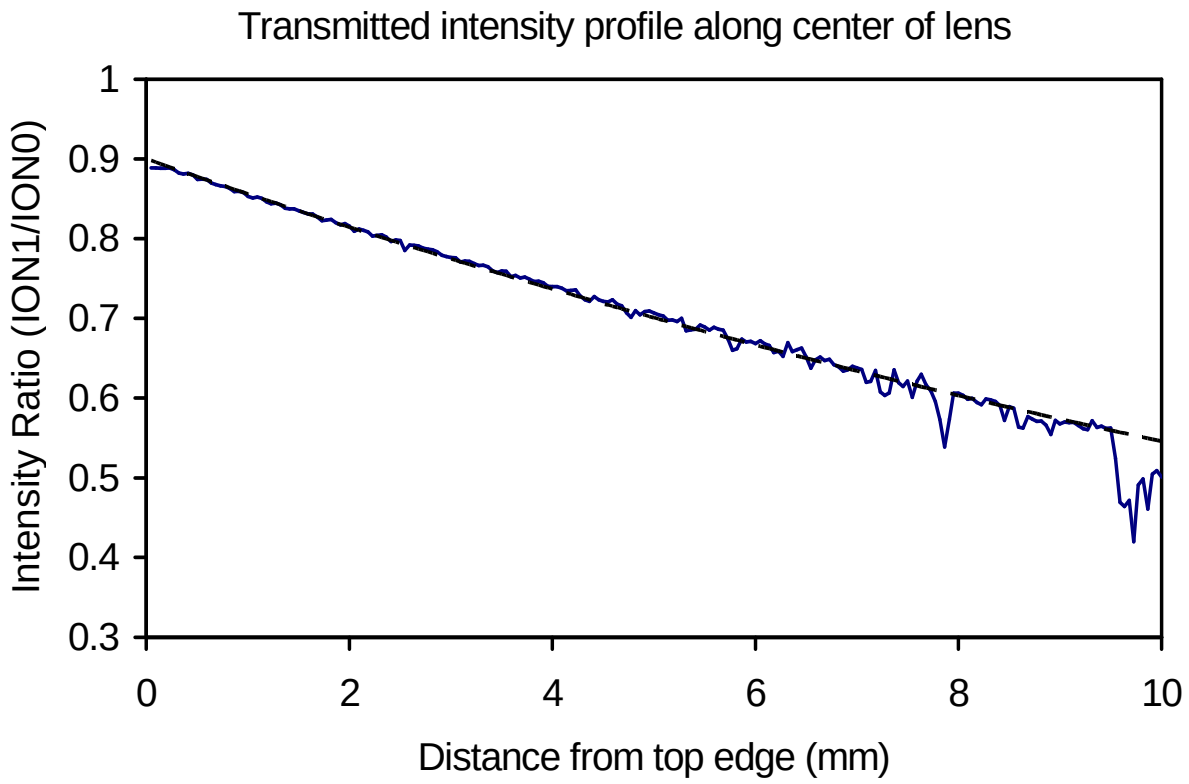

Figure 3: A line through a two-dimensional transmission map obtained by scanning the 50-lenslet lens is across a 50 μm x 20 μm incident X-ray beam. This line shows the beam normalized intensity going through the thinnest part of the lens, with no lenslets (extreme left) to 50 lenslets (on the right) in the beam. Attenuation in air is evident from the maximum normalized intensity of 0.9 in this figure.