Fabrication of Refractive X-ray Lenses by Ultradeep X-ray Lithography

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Introduction

In the hard x-ray domain, refractive lenses have specific design rules due to the close-to-unity values of the refraction index for most of the materials. In order to bring the values of the focusing distance down to 1-2 m, while keeping the absorption and scattering in the material of the lenses still low, one solution is to assemble many (tens to hundreds) microlenses in a row. Lenses of this type have been fabricated by mechanical means[1,2] or by micromachining.[3,4] We fabricated cylindrical microlenses of this kind by ultradeep x-ray lithography (UDXRL) in PMMA. Although the PMMA lenses have a limited lifetime in the x-ray regime (up to a dose of about 2000 J/cm^3), there are great advantages with our technology: direct quantity replication, high aspect ratio by use of thick PMMA (up to 6 mm), easy production of any type of optical figure. There is also the potential for replication of lenses by electroforming and injection molding.

Design, Fabrication, and Testing of the Lenses

The lenses were designed for use with 10 keV photons. The refraction index of PMMA at this energy is $n - 1 = 2.67 \times 10^{-6}$. The paraxial radius of curvature the lenses is R = 1 mm. The thickness of each concave lens is 20 µm. The spacing between the microlenses (the thickness of the convex holes) is 300 µm. Design of the rows of lenses was done such that the number of the lenses can be chosen by cutting/breaking from the micromachined piece of PMMA. For evaluation purposes, two types of microlenses were designed: cylindrical lenses with a circular or parabolic base shape, both having the same paraxial geometry and forming entirely separate rows. The fabrication sequence involved two major steps: the fabrication of the x-ray masks and the fabrication of the PMMA lenses by UDXRL.

The x-ray masks were fabricated by two methods:

- optical lithography in thick resist and electroforming of 65 mm of gold, and
- soft x-ray lithography in 80-µm-thick PMMA and electro forming of 65 µm of gold; as a mask for the soft x-ray exposure, a built-on mask made also by optical lithogra phy and 3 µm gold electroforming was used.

The latter mask proved superior in performance due to a better sidewall profile of the gold absorber structures.

The exposures for UDXRL were performed in proximity mode at the 2-BM beamline of the APS, using a 1-mm C filter and a 0.15° grazing-incidence Cr mirror for selecting the beam spectrum. Developing was performed using the GG-GGRinse developer system, at 25°C. Lenses were fabricated using plates of PMMA with thickness of 1, 3 and 6 mm, supplied by Goodfellow (CQ grade) and Atohaas (3 mm), with similar results (Fig. 1). Testing the refractive lenses with monochromatic hard x-rays (Fig. 2.) produced an increase in flux density in the focal spot up to 5 times for a row of 150 lenses. The focusing distance was 1.31 m. The focus spot width (FWHM) was 17 µm for the circular and 8 µm for the parabolic lenses. This was much above the diffraction-limited spot size (<0.1 µm). The difference is attributed to geometrical aberrations and roughness on the lens surfaces. Improvement of the optical performance by reduction of these factors is in progress.

FIG. 1. Array of refractive lenses fabricated by UDXRL in a 3-mm-thick PMMA plate.

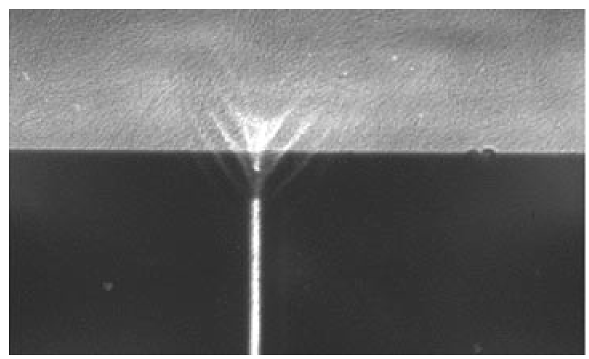

FIG. 2. Focusing of 10 keV x-rays.

Conclusions

Using UDXRL, we fabricated arrays of cylindrical compound x-ray lenses up to 6 mm height, with circular and parabolic surfaces. The measurements showed focusing down to 8 µm. The difference from the diffraction-limited focus size comes from aberrations and roughness on the lenses.

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References

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