KINOFORM LENSES - TOWARD NANOMETER RESOLUTION*

Aaron Stein^a, Kenneth Evans-Lutterodt^a, and Ashley Taylor^b

^aBrookhaven National Laboratory, Upton, NY 11973

^bLucent Technologies, Murray Hill, NJ 07974

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Kinoform Lenses – Toward Nanometer Resolution

Aaron Stein^{a*}, Kenneth Evans-Lutterodt^a, Ashley Taylor^b

^a Brookhaven National Laboratory, Upton, NY 11973

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Abstract: While hard x-rays have wavelengths in the nanometer and sub-nanometer range, the ability to focus them is limited by the quality of sources and optics, and not by the wavelength. A few options, including reflective (mirrors), diffractive (zone plates) and refractive (CRL's) are available, each with their own limitations. Here we present our work with kinoform lenses which are refractive lenses with all material causing redundant 2π phase shifts removed to reduce the absorption problems inherently limiting the resolution of refractive lenses. By stacking kinoform lenses together, the effective numerical aperture, and thus the focusing resolution, can be increased. The present status of kinoform lens fabrication and testing at Brookhaven is presented as well as future plans toward achieving nanometer resolution.

Keywords: Hard x-ray focusing, kinoform lenses

1. INTRODUCTION

The growing worldwide availability of high-brightness synchrotron radiation in the hard x-ray regime has increased the demand for high resolution focusing optics. Because the wavelength of hard x-ray photons ($E > 4$ keV) is on the order of angstroms, imaging applications with such coherent, wavelength-tunable radiation is typically limited by the focusing optics. Sub-micron resolution has been achieved in this region with reflective mirror pairs [1], diffractive Fresnel zone plates [2], refractive parabolic lenses [3] and compound refractive lenses (CRL) [4] as well as multilayer Laue lenses [5].

The resolution of zone plates is on the order of the outermost zone widths, *i.e.* the smallest fabricated feature and therefore ultimately offer diffraction-limited focusing. However, their efficiency is dependent on the zone thickness [6] and therefore the overall lens performance is limited by the highest achievable aspect ratio. For example, for 10 keV photons, a zone plate with 20% diffraction efficiency requires zones that are a micron thick. Therefore, to achieve a 50 nm spot, a challenging aspect ratio of almost 20 is required.

As with its optical counterpart, the resolution of purely refractive lenses for x rays is dependent on the effective numerical aperture. For refractive lenses, this aperture is limited by the absorption of the lens material. Reduced absorption can be achieved by using low-Z materials such as beryllium [7] but because of the small difference between the refractive index of vacuum and most materials for hard x-ray photons, small radii of curvature of the lens profile are required. These small radii of curvature are difficult to fabricate. Stacks of individual lenses with larger radii of curvature that are easier to fabricate can then be assembled into a compound refractive lens (CRL) with small effective radius of curvature [4]. The use of multiple lenses in CRL's does not resolve the loss issue and ultimately the effective aperture is limited by absorption, and this in turn limits the resolution obtainable by purely refractive means (figure 1).

Kinoform lenses substantially reduce the effect of absorption on lens resolution. Kinoforms offer resolution commensurate with fabricated feature size, but with theoretically achievable focusing efficiencies of over 90% [8]. To overcome the absorption of a typical refractive form and achieve such high efficiencies, we take advantage of Fresnel's observation that, in the refractive limit, the focusing properties of a lens are due only to the overall phase change caused by the curvature of the lens profile. The removal of all material causing 2π phase shifts does not change the overall lens properties for photons with the design energy, while greatly decreasing the absorption due to the optic. A more detailed description of the kinoform lenses used in this paper is described in reference [8]. A cross section of a kinoform lens, as compared to a purely refractive lens is shown in figure 2. The discrete jumps in the thickness of phase-shifting material are analogous to the discrete phase jumps of a binary Fresnel zone plate, but with the continuous phase change within each zone, similar to the continuous phase change of a refractive optic. This optics hybrid, which can be viewed from

* Corresponding author: stein@bnl.gov

both the diffractive and refractive points of view results in improved efficiency compared to binary zone plates with a binary phase profile.

Radially symmetric kinoform lenses can be designed to have a wavelength limited resolution as we show later in the text. However, the fabrication of radially symmetric kinoform optics is difficult due to the three-dimensional lithography and fabrication required. One approximation of radially symmetric kinoform lenses are blazed zone plates [9] which have been fabricated for soft x rays by DiFabrizio *et al.* using multiple electron beam lithography steps which must be aligned with high accuracy [10]. So far the technical challenges have limited developments in this direction.

We have chosen to manufacture kinoform lenses with standard microfabrication technology, and since this is typically a planar technology, we obtain cylindrical lenses, with a line focus instead of a point focus. To generate a point focus, we use a crossed pair of cylindrical lenses [11] (figure 3).

2. FABRICATION AND PERFORMANCE OF KINOFORM LENSES

To achieve the lowest absorption possible, a low- Z material is ideal for lens fabrication. To this end, beryllium, carbon or even lithium would be a desirable option, but handling and manufacturing of these materials is difficult. On the other hand, silicon is not prohibitively absorptive for multi-keV photons and is the subject of rich and successful fabrication techniques due to its ubiquity in semiconductor processes.

We desire high placement accuracy of lens features and patterns written over large areas with minimal displacement or distortion, so electron beam lithography (EBL) is used to generate the kinoform patterns. A silicon wafer (200 mm) is prepared with 100 nm of silicon dioxide and 200 nm aluminum nitride. An ARC coating is spun on the wafer as a protective layer for subsequent processing. A JEOL JBX-9300FS 100 keV EBL tool is used to expose

kinoform patterns in UV113 (Shipley) chemically amplified, positive-tone resist. After a post exposure bake at 130C for 90 seconds, the resist is developed in a tetramethyl ammonium hydroxide (TMAOH) solution (NMD-3 Ohka) for 90 seconds and rinsed in water.

The ARC coating shields the nitride mask from the base development. Since a positive resist is used as an etch mask, the areas around the lens are exposed, defining a channel around the optic. After etching, the channel effectively acts to aperture the lens allowing for easy alignment in the synchrotron beam and mating of two crossed-pair lenses. After the mask is etched, the lens pattern is deep-etched into silicon using the Bosch process [12]. Etch depths of more than 80 microns have been achieved. An example of a kinoform lens in deep etched silicon is shown in figure 4.

Figure 5. Knife-edge scan of kinoform lens. A copper knife edge is scanned with 500 nm steps through the focused beam of a single lens and the fluorescence signal is collected. The fit for this curve gives a submicron resolution measurement. The units on the x-axis are millimeters; the intensity on the y-axis is in arbitrary units.

knife edge in fluorescence. The measured resolution of the best knife edge scan is ~600 nm (figure 5). We have also generated a 2-D focused spot using a crossed pair arrangement (figure 6)[11].

There are several issues needed to be addressed in future measurements. There is a large amount of vibration noise inherent to the beamline, mostly due to the LN₂-cooling of the monochromator. We hope to address this in future tests. Another issue is the asymmetry of the incoming x-ray beam due to the undulator/synchrotron source – the beam is much smaller in the horizontal than the vertical direction. For a real-imaging system, lenses will need to be optimized for each direction and some post-processing will likely be necessary.

The kinoform optics are tested at the National Synchrotron Light Source (NSLS) at Brookhaven National Laboratory. We use a microdiffraction endstation at beamline X13B uses a mini-gap undulator and a double crystal Si <111> monochromator tuned to 11.3 keV. Lenses, either singularly or in crossed pairs, are mounted on picomotors situated on a vast array of translational and rotational stages. By imaging the transmitted x rays on a fluorescent YAG crystal with a CCD camera, the lenses can be aligned and focused in the beam. An aperture is defined both by slits in the beam and the self-contained channels of the fabricated optics. The resolution of the kinoform lenses is measured by scanning a knife edge through the beam and collecting transmitted with an integrating detector or collecting a fluorescent signal with a silicon fluorescence detector. So far, our best results are from scanning a patterned germanium

Figure 6: Crossed pair of kinoform lenses X-ray radiation through the lenses excites a YAG crystal and the resultant optical signal is magnified by a 10x objective and then collected by a CCD camera. The camera signal is averaged over multiple images to reduce background. Left image shows the two lenses before they have been crossed. Note that the vertical lens is better focused. These lenses have not been designed to work in tandem in a crossed pair. In the right image, the lenses are brought together to create a single 2-D focus.

3. NANOMETER RESOLUTION, LIMITATIONS AND FUTURE WORK

The lenses fabricated thus far are a work in progress to push the smallest focused spot toward nanometer length scales. As was pointed out initially [8], the aperture of a single kinoform lens is no longer limited by absorption, and is instead limited by the critical angle. This limited aperture results in a limited optic resolution of $\lambda/\theta_c = \lambda\sqrt{2\delta}$; this was also pointed out subsequently by Bergeman et al [13] in a different context. However, as was also realized in reference 8, this λ/θ_c resolution limit is not a fundamental limit, and by using multiple kinoform lenses, this resolution limit can be exceeded (figure 7). This was also subsequently realized by Shroer et al [14]. A compound kinoform lens of N lenses can produce a spot of size $\lambda/N\theta_c$; clearly by increasing the number of lenses one could finally run into the true far field resolution limit, the wavelength of the photons focused. The limitation, once again, is due to the loss introduced by each lens, leading to a signal-to-noise limit, not a resolution limit.

Figure 7. To achieve higher resolution, multiple lenses together in series. This serves to effectively increase the numerical aperture by a factor equal to the number of lenses. Each lens is designed to accept the incoming focused light from the previous lens as seen in the figure. Calculations show that the resolution limit of a single lens fabricated in Si is ~ 40 nm, so, in theory, 4 lenses stacked together could give ~ 10 nm resolution.

A fundamental limitation to our approach of the crossed-pair of cylindrical lenses is the breakdown of the Fresnel approximation. In the Fresnel approximation, spherical secondary wavelets are replaced by wavelets with parabolic wavefronts. Following Goodman, the starting point for such an analysis is the Fresnel-Kirchoff diffraction formula. If one makes the usual approximation of a “thin” optic, then, following Goodman [15], one has an equation of the form:

$$U(P_0) = \frac{1}{i\lambda} \iint_{(\xi,\eta)} U(P_1) \frac{\exp(ikr_{01})}{r_{01}} \cos \theta ds$$

where $k = \frac{2\pi}{\lambda}$, and $r_{01} = \sqrt{z^2 + (x - \xi)^2 + (y - \eta)^2}$ with (x, y, z) in the image plane and (ξ, η) in the “thin” object plane. One can expand r_{01} in a series, and retaining terms to 2nd order brings us to the Fresnel approximation for r_{01} :

$$r_{01} \approx z \left[1 + \frac{1}{2} \left(\frac{x - \xi}{z} \right)^2 + \frac{1}{2} \left(\frac{y - \eta}{z} \right)^2 \right]$$

showing the replacement of the spherical wave by a pair of orthogonal parabolic terms. Within the limits of validity of this approximation, the crossed linear pair are separable, and each lens focuses independently of the other. By examining higher order terms that were neglected, one can show that the limit of validity of this approximation is:

$$z^3 \geq \frac{\pi}{4\lambda} [(x - \xi)^2 + (y - \eta)^2]^2$$

We pick λ of order 0.1nm, and an aperture of 100 microns, which is a typical aperture size for our current lenses. We find that z , or the lens focal distance is greater than or equal to 1cm, corresponding to a diffraction-limited focused spot size of order 10 nm. In other words, for 100 micron aperture lenses, we expect a crossed lens pair to at least be able to focus down to 10 nm. However, this condition is sufficient, and is perhaps overly stringent; numerical simulations will be required to clarify the true limits of the crossed pair as an approximation to a radially symmetric lens.

Another shortcoming of the kinoform lens as compared to Fresnel zone plates or purely refractive lenses is their chromaticity. The optics, with their discrete jumps based on phase shifts, are designed for a single energy. Figure 8 shows the resulting spot size degradation as we focus a kinoform lens that was designed for operation at 11.3 keV across a range of energies [16]. This is one limitation that we cannot overcome in lens design, but one workaround we have is to put multiple lenses at key energies on one chip allowing quick changes between lenses; by keying on specific absorption energies with some previous knowledge about a specific sample's composition, chemical mapping can be done with an array of lenses.

Additionally, there are technical limitations to the kinoform performance. The total loss will depend on what the lens is made of and how much material is used to fabricate the kinoform. In theory, one can remove all 2π -phase shifting material from the lens structure to reduce loss to the minimum. Since we seek to maximize the aperture and the amount of light collected by the lens, and since we are using a crossed pair of optics, the lenses must be etched as deeply as possible. The best possible situation is for the etch depth to be equal to the width of the lens, which is on the order of 100 μm or more. Our hope is to continue to push the etch depths to increase the amount of light collected as much as possible. With such deeply etched features, we run into issues of aspect ratio limitations and ultimately pattern collapse, but presently we are mostly limited by the etch undercut (figure 9). To rectify this problem, we can design

lenses with more material – keep adding material representing multiples of 2π phase shifts until the features are large enough to withstand our aspect ratio limitations.

Of course, the addition of material brings us back to more loss and there will ultimately be a compromise position. We are in the process of making measurements that we hope will tell us more about how much real loss we incur each time we add more material to the lens design as well as how much additional loss we get as lenses are stacked together. Since the theoretical efficiencies at some energies are upwards of 90%, we suspect that the additional material will not introduce a prohibitive loss. Ultimately, the move to alternative materials, such as diamond [17] or beryllium will likely be considered as a means of reducing the loss incurred from stacks of multiple lenses.

Since the kinoform is a phase-modifying object, precise control of the phase profile across the entire lens aperture is important. The required precision of pattern placement can best be satisfied by electron beam lithography. Since the lenses can be on the order of several millimeters long, they extend beyond a single writing field of all EBL tools and high-accuracy field-stitching is required. The 500 μm field size and the laser-interferometer stage of the JBX9300-FS allow for areas of millimeter scale to be precisely patterned.

Figure 9. Scanning electron micrograph of the smallest features of the etched kinoform. The limits of the deep etch are dictated by the undercut. For a given etch depth, there is a limit to the smallest feature size achievable. To circumvent this issue, the lens must be designed with more multiples of 2π phase-shifting material. The oxide mask is still intact and is visible in the image.

4. CONCLUSION

The kinoform lens represents one of the best opportunities for nanometer-scale spot sizes for hard x-rays. The reduced loss from the removal of redundant phase-shifting material leads to lower losses than refractive lenses and extremely high focusing efficiencies. With lower losses, many lenses can be stacked together in serial to increase the numerical aperture and thus the resolution. While present-day deep-etched silicon kinoforms show promise, we continue to work to improve the etch depth, the quality of the lenses and hope to seek out methods for producing lenses in lower-Z materials. In addition, current studies are in progress to determine the improvement on resolution and the increment of losses as we begin to stack lenses as well as add material to overcome aspect ratio limitations. Even with improvements to the present approach described above, lenses produced using such planar fabrication techniques will only generate cylindrical lenses which focus in a single dimension. The crossed pair of kinoform lenses can produce a 2D spot, but with some limitations. The ultimate goal of this work is to find a path toward fabricating three-dimensional, radially symmetric lenses giving a true point focus.

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