Highly efficient 2-D nano focusing by an optical system of planar refractive lenses

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Abstract. A lens system of two parabolic refractive X-ray lenses giving an intensity gain over 10\textsuperscript{8} for a focal spot size below 10 nm for photon energies above 10 keV is suggested.

1. Introduction

A large number of experiments in X-ray spectroscopy and X-ray imaging with microprobes require, because of their structural complexity, dispersion and separation into voxels below 1 µm [1, 2]. This can be solved using an X-ray beam focused into a nano spot. This requires a decrease in the focal distance of the refractive lens, resulting in a reduced lens aperture, and consequently a reduced photon flux. We develop an X-ray lens system containing two refractive lenses, and providing nano focus spot and high flux to a microprobe, simultaneously.

2. The lens system arrangement

It is known from the theory of refractive optics that the effective aperture \(A\) for linear focusing lens increases as [3]:

\[
A = 0.707 \sqrt{\beta \cdot \lambda / f / \delta}
\]

where \(\lambda\) – wavelength and \(\beta, \delta\) are absorption index and refractive index decrement in the index of refraction \(n = 1 - \delta + i\beta\) of the lens material. This requires increasing a focal distance \(f\), but at the same time, the focus spot \(\sigma\) will be increased as:

\[
\sigma = 0.664 \sqrt{\beta \cdot \lambda / f / \delta}
\]

One possible solution is to install two refractive lenses, namely the first of them downstream the X-ray beam as a condenser lens collecting the incoming radiation onto the entrance of the second lens called objective lens, as shown in Fig. 1.

![Fig. 1. Schema of the optical design.](image-url)
The objective lens is positioned at the focal plane of the condenser lens and covers the length of focus waist. This waist length can achieve, for a highly coherent X-ray beam, several millimetres. The resulting intensity gain for a system of two crossed lenses in paraxial approximation is:

\[
G = 0.56 \frac{f_2 \cdot \delta_1 \cdot \delta_2}{f_1 \cdot \beta_1 \cdot \beta_2} \exp\left(-\mu_1 \cdot d_1 - \mu_2 \cdot d_2\right)
\]

where \(\mu\) – linear absorption coefficient, \(d\) – total length of bridges between parabolas, \(\beta_1, \delta_1, \mu_1\) and \(\beta_2, \delta_2, \mu_1\) belong to the condenser and objective lens material, respectively. Typically, the distance \(f_2\) is \(-\) in accordance to the beam line setup (hutch) \(-\) between 1 meter and 4 meters. The other values are defined below.

2.1. Lens design
The condenser lens and the objective lens have been developed and manufactured at the Institute for Microstructure Technology (Karlsruhe) by means of LIGA processes including deep X-ray lithography at ANKA synchrotron source [4].

2.1.1. Condenser lens. To achieve higher intensity at the focus spot, an X-ray condenser lens has been developed of SU-8 polymer, showing high radiation-damage stability, Fig. 2a. Tilted in two directions i.e. \(+45\) and \(−45\) degrees, the combination of two linear lenses produces a point like focus spot, Fig. 2b. As 16 lenses are fabricated on one wafer, 16 different photon energy-focal distance combinations can be realized on one wafer.

![Fig. 2. Condenser lens inspection: a) electron microscopic picture of focusing tilted micro structures of one half of the condenser; b) measured focus spot on the detector screen for a photon energy of 20 keV and focal distance of 870 mm, the image field is 10 × 10 pixels, where 1 pixel = 660 × 660 nm.](image)

2.1.2. Objective lens. Lenses with a very small radius of curvature and of heavy material as nickel, providing the shortest possible focal distance have been considered, Fig. 3. A short lens of SU-8 in comparison to a nickel lens becomes significantly more transparent for the outermost rays, for the energy range marked below. For this reason a prolongation of a SU-8 lens due to increasing the radius of curvature to several micrometers offers the possibility to enlarge the lens aperture by using a Fresnel-like truncated profile, Fig. 4.

The compact arrangement of focusing microstructures on a wafer provided by deep X-ray lithography gives several hundred micrometers long nickel lenses and several millimeters long SU-8
lenses. In accordance with formula (3) the resulting intensity gain lies between $10^7$ and $2 \times 10^8$ for $f_2=1$ m and $f_1$ in the millimeter range.

Now, manufactured condenser and objective lenses have been equipped with very precise translation tool for testing.

![Image of lens structure](image)

Fig. 3. Light microscopic image of the minimum radius of curvature achieved in SU-8 microstructures; this radius could be realized as radius of curvature of the last focusing elements of linear objective lenses.

![Graph showing FWHM and energy](image)

Fig. 4. Calculated diffraction limit and dimension of the demagnified source projection for ESRF (60 µm source size, 60 m long beam line) and ANKA synchrotron sources (200 µm source size, 11 m long beam line), and for an objective lens made of SU-8 respectively nickel as a function of the photon energy.

3. Summary
A new optical system of two refractive planar X-ray lenses has been described. A SU-8 polymer lens precisely structured by means of LIGA allows achieving an extremely high aperture of a condenser lens. For the focusing lens a crossed planar parabolic lens of heavy materials as nickel provides a lower diffraction limit of the spot size and high stability under the increased photon flux. The simulated gain is over one hundred million in the focus spot of several nanometers in size.

References
[1] O’Day P, Carroll S A, Bajt S 2003 Comparison of Synchrotron X-ray Fluorescence Mapping and Micro-XANES to Bulk X-Ray Absorption Spectra in Metal-Contaminated Sediments Lawrence Livermore National Laboratory Report UCRL-ID-151516 http://www.doc.gov./bridge
[2] Hoppe P 2008 Astronomical Society of the Pacific Conference Series 309 265
[3] Kohn V 2003 Journal of Experimental and Theoretical Physics 124 1-13
[4] Nazmov V, Reznikova E, Somogyi A, Mohr J, Saile V 2004 Proc. SPIE 5539 235-243