ESRF	**Experiment title:** X-ray waveguiding using convergent beams	**Experiment number**: MI-471
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Report

Previously, we have developed a tunable x-ray waveguide [1,2] to perform dynamic and static x-ray diffraction experiments on thin fluids confined within the guiding layer of the waveguide. The typical waveguide gaps are between 50 nm and a few microns. Since the scattering volume decreases at decreasing gap width and the electron-density contrast is very small for some very interesting systems, the scattered intensity can be extremely low.

In order to enhance the flux inside the waveguide, we used a one-dimensional transmission Fresnel zone plate (FZP) lens to focus x rays of an energy of 13.3 keV onto the entrance of our x-ray waveguide. The rays are incident from the side under a grazing angle (see Fig. 1). Fig. 2 shows a scanning electron micrograph of the FZP-lens. The structure was patterned by use of electron beam lithography and subsequent wet chemical etching of a <110 >-oriented silicon substrate, allowing for a high aspect ratio of the outer Fresnel zones. The height of the ridges is 5.5 μm.

At 13.3 keV, the path length difference between the trenches and ridges should be 16.8 μm in order to obtain a phase shift π which yields the maximum efficiency of the lens. By rotating the orientation of the lens by 70.9 degrees, we can tune this path length difference to this optimal condition. The tunability of the lens makes the lens suitable for a large energy range. This method is described more elaborately elsewhere [3]. We found an experimental lens efficiency of 32.6%, which is comparable to the maximum theoretical efficiency for a perfect lens of 37.4% when taking absorption into account.

In Fig. 3, the transmitted intensity through a waveguide of 300 nm width is shown as a function of the vertical lens position. The maximum flux enhancement inside the waveguide is a factor 54 and the FWHM is 1.03 μm. This width corresponds to the gain factor 54, if a Gaussian shape of the image at the waveguide is assumed.

In Fig. 4, the numerically calculated and the measured far field intensity distributions $I(\theta_i, \theta_e)$ are shown as a function of incidence angle θ_i and exit angle θ_e. The waveguide gap width is 957 nm. The different waveguide modes show up as maxima along the diagonal. The horizontal width of the diagonal corresponds

to the angular distribution expected from the lens height and focal length. Also, along the diagonal a weak beating period can be seen, which is indicative of multimode interference. This reduced visibility is an indication that the beam is partially coherence. The vertical transverse coherence length in our situation was 80 microns at the position of the lens, which itself is 200 micron high. At large waveguide widths, the intensity in the waveguide is not fully coherent, while at gaps much smaller than 350 nm (the outermost zone width), the intensity is fully coherent in the vertical direction.
The results of this experiment show that it is possible to enhance the flux inside a planar waveguide by a factor 54, and at gap settings below the outermost zone width, the intensity is still fully coherent. This enables a large range of coherent scattering experiments to be performed in small scattering volumes at greatly enhanced flux.

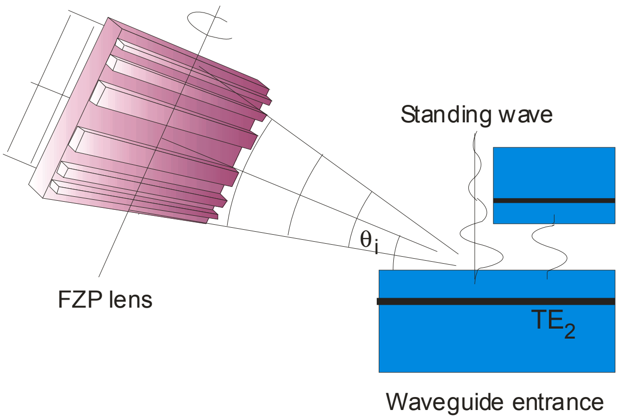

Fig. 1 Schematic of the experimental setup. The FZP-lens focuses a 200 micron incident beam into a ca. 1 micron size spot at the entrance of the waveguide, where the waveguide modes are excited. By rotating the lens around its axis, the phase shift between the trenches and ridges can be tuned to the desired the photon energy. The focal length of the lens is 74 cm at 13.3 keV.

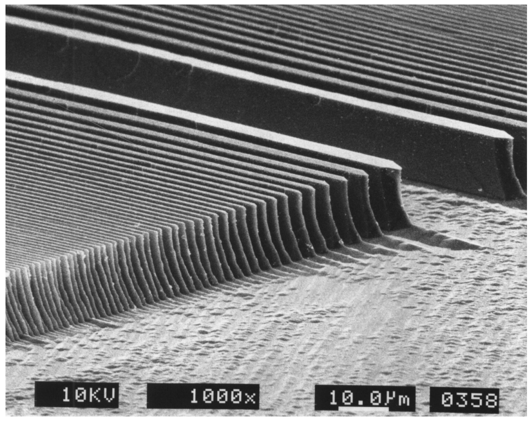

Fig. 2 Electron micrograph of a one-dimensional zone plate lens, which is used to focus the beam. The lens consists of a rectangular pattern of trenches and ridges on a 5 µm thick silicon membrane. The outermost zone width is 350 nm. The height of the ridges is 5.5 µm. The lens size perpendicular to the stripes is 200 µm and along the stripes 2.5 mm.

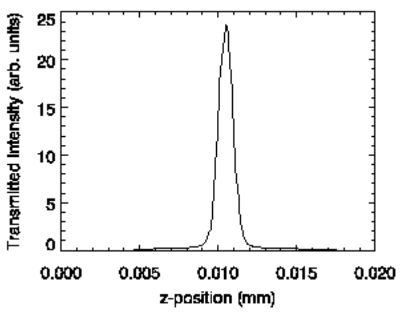

Fig. 3 Total transmitted intensity through the waveguide as a function of the vertical lens position z for a waveguide gap *W*=300 nm. The profile represents the image of the undulator source, convoluted with the gap with of the waveguide and the diffraction limited resolution of the FZP lens.

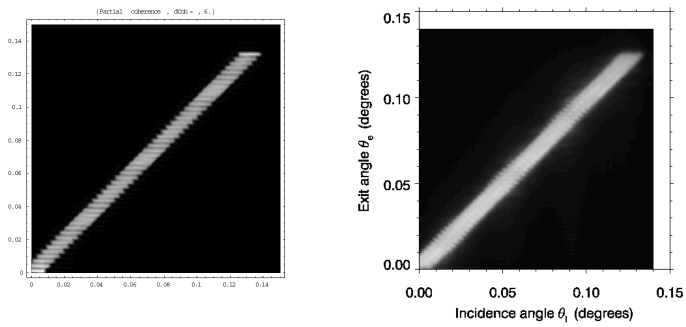

Fig. 4 The intensity distribution in the far field $I(\theta_i, \theta_e)$ as a function of incidence angle θ_i and exit angle θ_e for a 957 nm waveguide gap with a prefocused beam. To the left is shown a numerical calculation for a partially coherent beam, as expected from the beam properties. To the right are shown the experimental data. The broadened diagonal is caused by the angular distrinution in the converging focused waves.

References

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