



## CLESSIDRA: tiny refractive plastic lenses for focusing x-rays.

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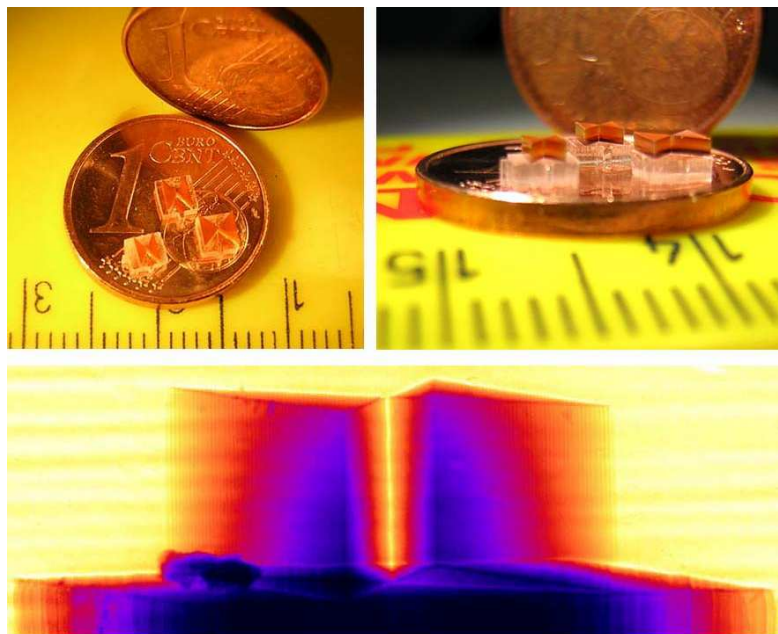
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The pictures shown here in figure 1 present a few prototypes of an innovative refractive lens, which can focus or collimate x-rays. Up to only 8 years ago refractive lenses for x-rays with photon energies of several keV were not found worth consideration (find the short history in the appendix) even though their insertion into an existing instrument is a relatively simple task. This has completely changed recently, as the group of Professor B. Lengeler from the RWTH in Aachen (Germany) could obtain a state-of-the-art spatial resolution below 100 nm with a stack of many small concave transmission lenses, the so called compound refractive lenses (CRL) [see [http://www.sri2003.lbl.gov/pdf/Lengeler\\_Talk7.3\\_SRI03.pdf](http://www.sri2003.lbl.gov/pdf/Lengeler_Talk7.3_SRI03.pdf) ]. Actually it turns out that the requirements for the surface quality for these x-ray lenses can be less stringent than they are for lenses for the visible range, which is due to the small refractive index for any material in the x-ray range. The contrary is true e.g. for x-ray mirrors and it is responsible for the slower progress towards diffraction limited focusing with these objects.



**Figure 1:**

Top row: 3 clessidra lenses with (from left to right) 1.5 mm, 1.8 mm and 2.6 mm geometric aperture positioned on a 1 Eurocent coin. The lenses will focus x-rays, which travel parallel to the coin surface and parallel to the long prism base.

Bottom row: False-colour high resolution radiograph from the smallest lens registered with a special CCD camera at SYRMEP@ELETTRA. The lens orientation is the same as in the right picture from the top row.

The rather relaxed requirements for the perfection of the refracting surface in x-ray transmission lenses do not require sophisticated polishing processes anymore, but are feasible with standard workshop tools and lithographic processes. The development of the presented lenses was thus driven with this in mind and by the following requests for their optical performance:

- minimize the amount of refracting and absorbing material to be passed by the x-rays for maximizing the transmission
- maximize the size of the smallest features in the lens for maximizing the possible structure height and stiffness
- minimize the focal length of the lens for minimizing the demagnified source image
- maximize the aperture of the lens for minimizing the diffraction limited image size
- minimize the distortions that the lens will introduce into the planes of equal phase of the passing x-rays for minimizing the diffraction limited image size.

The latter request is satisfied when the amount of refracting material follows a parabolic dependence with distance from the optical axis of the lens and when the phase retardation in the wavefield at any material discontinuity is an integer multiple of  $2\pi$ .

All these requests could be accommodated in a rather compact small lens, which has a quite unusual structure and which does not have similarities anymore with other objects known from classical optics. Indeed many small prisms, which give rise to the periodic vertical line structure in the presented radiograph, form two large prisms (the brownish prisms of 1 mm height in the top row of figure 1), which almost touch at their tips. From this lens shape, which recalls a sandclock, the project received its Italian name CLESSIDRA. The CLESSIDRA structure can form an x-ray transmission lens for one-dimensional focusing free of aberrations, which is the last requirement from above, if a few of the side surfaces of the smaller prisms are slightly curved. The free size parameters of this concept were adjusted to dimensions, which can routinely be realized with deep x-ray lithography (DXRL).

The lenses plus their supports measure only 3 mm x 3 mm x 2 mm and are produced in SU-8 photoresist, i.e. in a plastic, on a 1 mm thick sheet of transparent plexiglass (PMMA). These lenses are chromatic and the largest lens focuses Cu  $K_{\alpha}$  radiation (8.05 keV photon energy) with focal length  $f=2.18$  m. Note that it needs a 260 mm long mirror for intercepting the same beam height.

This prototype lens provided at the SYRMEP beamline at ELETTRA a gain (i.e. ratio of the photon densities at a given source distance with the lens and without it) of 10 in a line focus with width 50  $\mu\text{m}$ . Instead in a crossed lens configuration for two-dimensional focusing as shown in figure 2 the gain was 25 in an almost circular spot of 55  $\mu\text{m}$  height and 80  $\mu\text{m}$  width

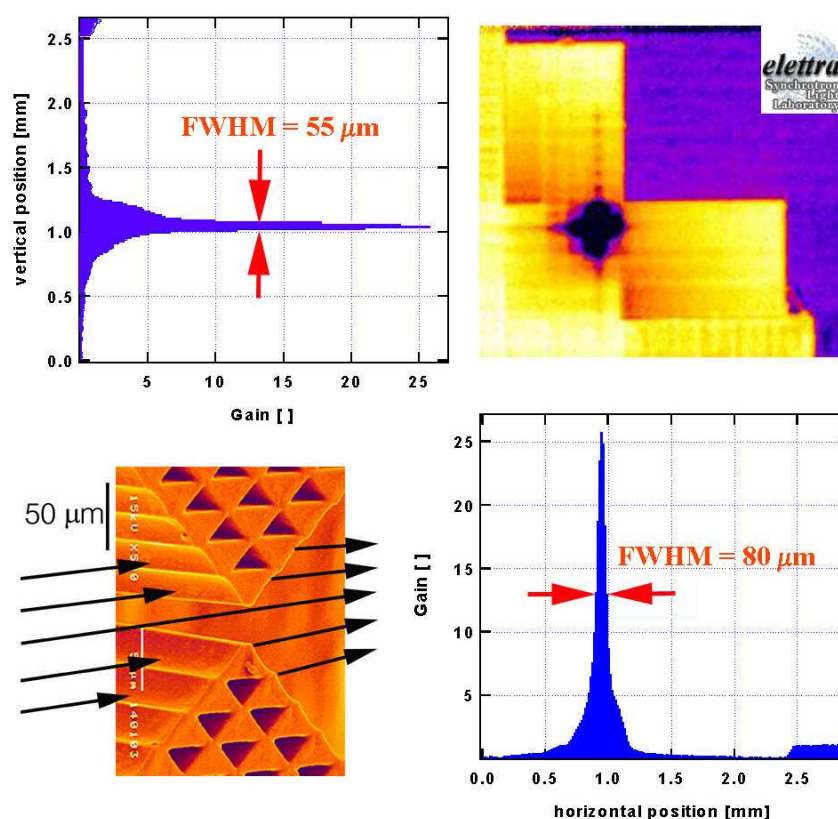
[see also <http://journals.iucr.org/s/issues/2004/03/00/issconts.html> ].

At ID22 at the ESRF a gain of 23 was found in a significantly smaller focus of 2.8  $\mu\text{m}$ . Ideally the demagnified source image in this case should have been 1.73  $\mu\text{m}$ . The discrepancy is mostly due to a rapid and rather "careless" alignment of the lens tilt and of the apertures in a short test run of a few hours, in which the image sizes

obtained behind several lenses were characterized with knife-edge scans at several distances from the lens.

The present lenses with still rather large focal lengths ( $f > 1$  m) have numerical apertures in the range 0.45 mrad to 0.6 mrad, which would allow a diffraction limited spot size for  $\lambda=0.154$  nm (Cu  $K_{\alpha}$  radiation) below 250 nm.

Find more details in the latest issue of Journal of Synchrotron Radiation [J. Synchrotron Rad. 11, 248-253 (2004) or <http://www.iucr.org/cgi-bin/paper?fd5003> ].



**Figure 2:**

Top right: Radiograph taken by use of a CCD camera in the focal plane of two crossed prism lenses of the type shown at bottom left with apertures of  $A=2.6$  mm. The vertically and horizontally focusing lenses are seen as yellow shadows created by the beam, which has blue-purple color. In the saturated black spot the lens provides an intensity gain of 25 in a full-width-at-half-maximum spot size of  $55 \mu\text{m} \times 80 \mu\text{m}$ , as can be derived from the vertical and the horizontal beam profiles positioned to the left and below the CCD picture, respectively. The prisms have uniform shape up to 0.4 mm depth. Consequently the lens combination has an acceptance of 0.4 mm x 0.4 mm, and the most intense focus is thus found at 0.2 mm from the lens surfaces.

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## APPENDIX: Short history of refractive lenses for the microfocusing of x-rays

C. W. Roentgen realized immediately that his x-rays were not refracted appreciably in any material. Consequently refractive x-ray lenses were not discussed for some time. Kirkpatrick & Baez [*J. Opt. Soc. Am.* **38**, 766-774 (1948)] knew already better the order of magnitude of the refractive index for x-rays, from which they derived focal lengths even for stacks of refractive lenses of the order of 100 m. Consequently they abandoned these lenses for the focusing of x-ray tube radiation, and they followed the concept of a crossed mirror pair instead. Only after the introduction of 3rd generation synchrotron radiation sources finally Suehiro et al [*Nature* **352**, 385-386 (1991)] found an application for x-ray lenses with very long focal lengths. In order to reduce the absorption off-axis in the concave lenses, they already discuss the use of Fresnel lenses, which they consider to be feasible by use of a lathe. Michette [*Nature* **353**, 510 (1991)] comments this latter study and favours Fresnel zone-plates for the soft x-ray region. Nevertheless Yang [*Nucl. Instrum. Methods* **A328**, 578-587 (1993)] systematically discussed the use and the technical feasibility of refractive x-ray lenses, and especially of the Fresnel version. However, it does not seem that Suehiro et al or Yang ever realized the objects that they discussed.

Finally starting in 1994 Tomie receives patent protection ["X-ray lens", Japanese patent 6-045288 (18 February 1994), US Patent No. 5,594,773 (1997), German Patent No. DE1995019505433 (1998)] for refractive x-ray lenses, which can be produced with little technical effort: drill a series of holes with very small diameter into material in order to create a stack of many identical concave lenses. Parallel holes will focus in one dimension and a system of holes with orthogonal axes will focus in two dimensions. Also he does not report the practical realization of his lens. Then only in 1996, 101 years after Roentgen discovered x-rays, Snigirev et al [*Nature* **384**, 49-51 (1996)] report data for the performance of the first practically realized refractive x-ray lenses for microfocusing. These lenses were identical to those described by Tomie and were given the name of compound refractive lenses CRL. Recently B. Lengeler et al could achieve very competitive spatial resolution with the CRL concept [[http://www.sri2003.lbl.gov/pdf/Lengeler\\_Talk7.3\\_SRI03.pdf](http://www.sri2003.lbl.gov/pdf/Lengeler_Talk7.3_SRI03.pdf)]. Their latest lenses are double concave with the ideal parabolic shape. These lenses are obtained by pushing two opposing stamps with the negative and rotationally-symmetric lens shape into small metallic platelets and they focus thus bi-dimensionally.

Aristov et al [*Appl. Phys. Lett.* **77**, 4058-4060 (2000)] succeeded by use of deep x-ray lithography to make the first functional concave Fresnel lens for focusing in one dimension. A stack of bi-dimensionally focusing concave machined Fresnel lenses is described by Pietrup et al [US Patent No. 6,269,145 B1 (31 July 2001)].

Cederstroem et al [*Nature* **404**, 951 (2000)] present rather strange, once widely distributed objects for focusing x-rays: pieces of old long playing records (LP). X-rays, which hit an LP at grazing incidence, pass through many small prisms and are then deviated by small quantities. Two small LP pieces, which form an open alligator mouth (Dufresne et al [*Appl. Phys. Lett.* **79**, 4085-4087 (2001)] refer to these lenses thus as alligator lenses), will then bring x-rays to a focus in one dimension.

CLESSIDRA then combines the advantageous features of the latter two concepts, however, with some compromise. Firstly, the clessidra lenses contain less absorbing material than CRL's with identical focal length, but more than equivalent Fresnel lenses. Secondly, the lens segments are of very simple shape and of rather large size, which facilitates significantly the quality control with standard optical instrumentation for lenses, which can be mass-produced by use of deep x-ray lithography.