How to make fruitful use of X-ray refraction

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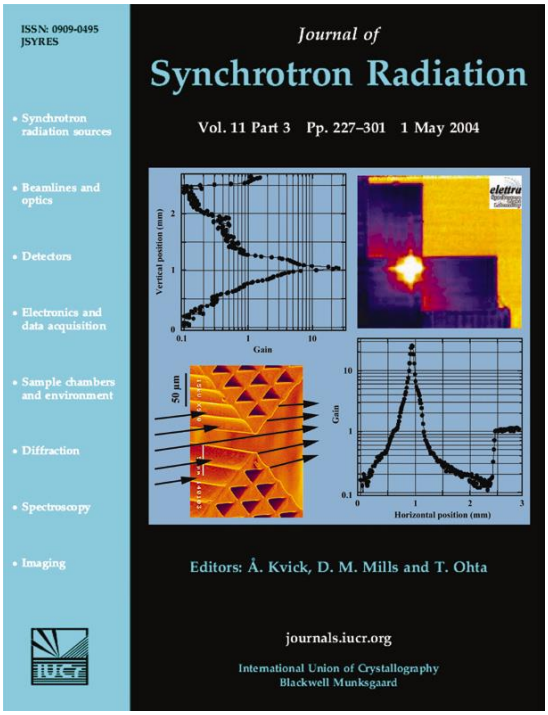
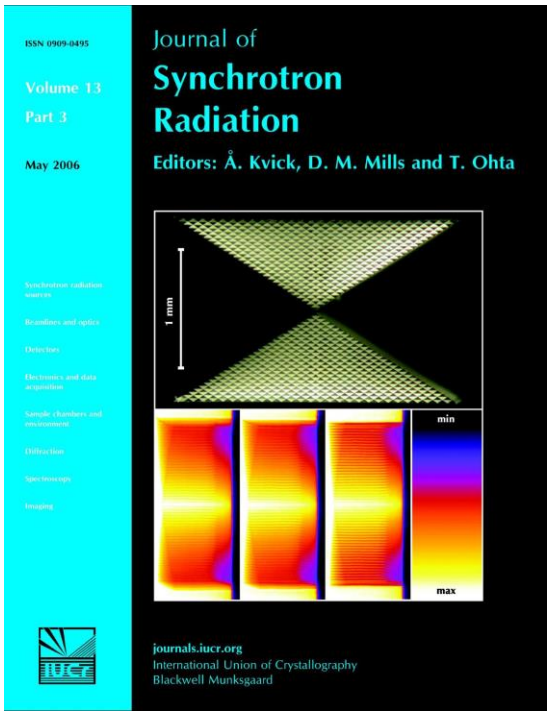
I started to work on this topic after I had attended, and appreciated very much, a seminar given by Björn Cederström in August 2000 at the SPIE International Symposium on Optical Science and Technology in San Diego, CA (USA). The seminar dealt with refractive X-ray lenses, which could be made from obsolete long playing records (LP) [B. Cederström, R.N. Cahn, M. Danielsson, M. Lundqvist & D.R. Nygren, "Focusing hard X-rays with old LPs," Nature **404**, 951 (2000)], and which for their appearance received later the name alligator lenses. I repeated part of Cederström's experiments at lenses, which were made in minutes on a lathe in a mechanical workshop [see chapter [0] in list at the end]. These experiments were meant as a proof of principle for a successive proposal for a cheap beamline/monochromator to be constructed from such lenses.

Refractive X-ray lenses always present an absorption limited aperture and thus I started to think about, how to remove some "useless" optically inactive material from the alligator lens [see chapter [1] in list at the end]. Simultaneously Cederström did obviously the same. The two solutions, which we presented are both based on regularly structured prism arrays, which were fabricated employing lithographic techniques. Our solution is highly symmetric, and as the final object resembles very much an hour glass, the project received as a name the Italian translation for the latter, i.e. Clessidra.



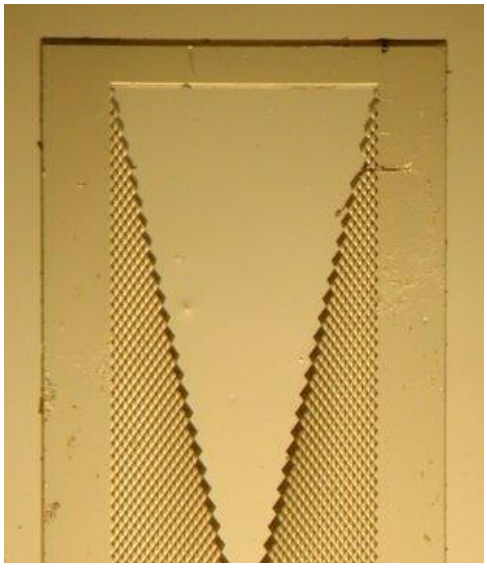


The photographs in the two journal covers on the previous page present details in such Clessidra prism arrays.

Left cover: False-colour CCD image taken in the focal plane of two crossed prism lenses, of the type shown at the bottom left, see Jark, Pérennès, Matteucci, Mancini, Montanari, Rigon, Tromba, Somogyi, Tucoulou and Bohic, pages 248-253. These lenses were produced at the deep X-ray lithography beamline of ELETTRA, and the CCD image was taken at the SYRMEP beamline at ELETTRA. The vertically and horizontally focusing lenses and their supports are seen as blue shadows in the yellow beam. The saturated white spot is the focus, in which an intensity gain of 25 is obtained (see the vertical and horizontal beam profiles). The single lens focuses one-dimensionally and thus, as is shown in the radiograph in the left photograph, two of them need to be operated in the crossed orthogonal orientation for providing two-dimensional focusing.

Right cover: The prism array X-ray lens clessidra developed at ELETTRA (Sincrotrone Trieste), see Jark, Pérennès and Matteucci, pages 239-252. Top: micrograph of the lens produced using deep X-ray lithography at the DXRL beamline at ELETTRA. The lens is made of pmma (polymethylmethacrylate = plexiglass) and consists of small prisms of height 25.67 µm and width 77.33 µm. The overall structure is 1.51 mm high, 2.6 mm wide and ~0.65 mm deep. Bottom: radiographs taken 30 mm downstream of the lens during the tilt alignment with a photon energy of 10 keV (tilt increment 1°). A CCD camera with 3.85 µm equivalent pixel size was used at the SYRMEP beamline at ELETTRA at a source distance of 22.6 m. In this lens the resist thickness varied in the beam direction.

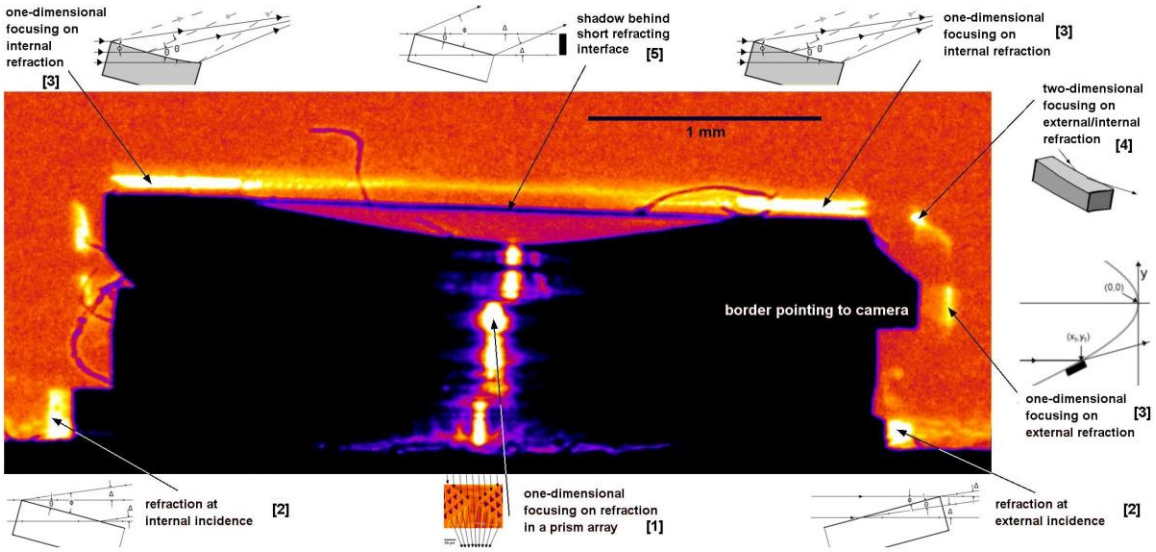
For a particular project the free standing prism structure was stiffened by preparing a frame around it as shown in the next figure (now the beam has to travel in the paper plane from top to bottom). The narrow horizontal stripe at the top has a height of 0.3 mm, while the corners are separated by 3 mm. In this case a large number of lenses were supposed to be stacked adjacent to each other, such that the assembly would provide a long line focus. During the tests on these lenses and on alligator lenses many more refraction phenomena were observed.



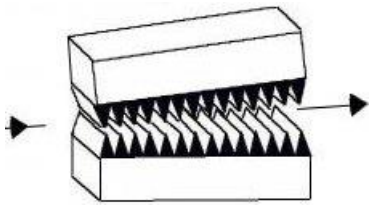
For a rapid characterisation of the lens properties, i.e. focal length and refraction efficiency, several of these latter lenses were just put rather carelessly on top of each

other and then a radiograph was taken behind this assembly. Neither were the lenses aligned well with respect to each other nor was the assembly put into the desired operation condition. Some lenses were bowing along the long surface, some remained flat. Consequently in the following radiograph of a misaligned lens stack of 3 lenses one can observe all the refraction phenomena, which are subject of my most recent publications, which are listed further down.

A handful of X-ray refraction phenomena in a single shot image from a stack of plexiglass prism array lenses



Phenomenon [0] (not in radiograph)**: X-ray focusing in one dimension in alligator lenses**

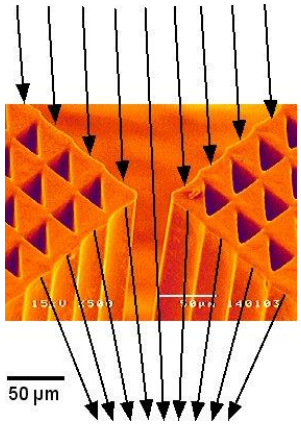


1.) **W. Jark**, *A simple x-ray monochromator based on an alligator lens*, X-ray Spectr. **33**, 455-461 (2004)

2.) **W. Jark**, *On aberrations in saw-tooth refractive x-ray lenses and on their removal*, J. Synchrotron Rad. **18**, 198-211 (2011)

3.) **W. Jark,** *High spatial resolution with zoomable saw-tooth refractive lenses?* SPIE - Proceedings: Advances in X-ray/EUV Optics and Components VI. Vol. **8139**, 81390W (2011)

Phenomenon [1]: X-ray focusing in one dimension in Clessidra prism arrays



1.) **W. Jark,** F. Pérennès, M. Matteucci, L. De Caro, *CLESSIDRA: focusing hard x-rays efficiently with small prism arrays,* **Modern Developments in X-Ray and Neutron Optics, Springer Series in Optical Sciences , Vol. 137, 331-351, Springer 2008 (ISBN: 978-3-540-74560-0)**

2.) **W. Jark**, F. Pérennès, M. Matteucci, L. Mancini, F. Montanari, L. Rigon, G. Tromba, A. Somogyi, R. Tucoulou, S. Bohic, *Focusing X-rays with simple arrays of prism-like structures,* J. Synchrotron Rad. **11,** 248-253 (2004)

3.) **W. Jark**, F. Pérennès, M. Matteucci, L. Mancini, F. Montanari, L. Rigon, G. Tromba, A. Somogyi, R. Tucoulou, S. Bohic, *Focusing hard x-rays with large kinoform lenses of mm size,* SPIE - Proceedings: Design and Microfabrication of Novel X-ray Optics II. Vol. **5539**, 59-72 (2004)

4.) F. Pérennès, M. Matteucci, **W. Jark**, B. Marmiroli, *Fabrication of refractive X-ray focusing lenses by deep X-ray lithography*, Microelectron. Eng. **78-79**, 79-87 (2005)

5.) **W. Jark**, F. Pérennès, M. Matteucci, *On the feasibility of large aperture Fresnel lenses for the micro-focusing of hard x-rays,* J. Synchrotron Rad. **13,** 239-252 (2006)

6.) **W. Jark**, F. Perennes, M. Matteucci, L. Mancini, R. H. Menk, L. Rigon, *CLESSIDRA: Focusing hard x-rays efficiently with arrays composed of small prisms,* "AIP Conference Proceeding 879 SYNCHROTRON RADIATION INSTRUMENTATION: Ninth International Conference on Synchrotron Radiation Instrumentation.", 796-799 (2007)

7.) L. De Caro, **W. Jark**, *Diffraction theory applied to x-ray imaging with clessidra prism array lenses,* J. Synchrotron Rad. **15,** 176-184 (2008)

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9.) L. De Caro, **W. Jark**, R. H. Menk, M. Matteucci, *Diffraction of partially coherent X-rays in clessidra prism arrays,* J. Synchrotron Rad. **15,** 606-611 (2008)

10.) **W. Jark**, M. Matteucci, R. H. Menk, L. Rigon, L. De Caro, *The role of spatial coherence, diffraction and refraction in the focusing of x-rays with prism arrays of the Clessidra type,* SPIE - Proceedings: Advances in X-ray/EUV Optics and Components III. Vol. **7077**, 70771X (2008)

11.) M. Simon, E. Reznikova, V. Nazmov, A. Last, **W. Jark**, *X-ray Prism Lenses with Large Apertures,* SPIE - Proceedings: Advances in X-ray/EUV Optics and Components III. Vol. 7077, 70771Q (2008)

12.) **W. Jark**, *On easily tunable wide-bandpass X-ray monochromators based on refraction in arrays of prisms*, J. Synchrotron Rad. **19** (4), 492-496 (2012)
13.) **W. Jark**, *Concepts for flexible and efficient monochromatization of X-rays by refraction to a relative bandwidth of the order of 0.5%*, J. Synchrotron Rad. **20** (1), 190-193 (2013)
14.) **W. Jark**, A. Last, *Concepts for rapid tuning and switching of X-ray energies*, SPIE - Proceedings: EUV and X-Ray Optics: Synergy Between Laboratory and Space III, Vol. **8777**, 877712 (2013)
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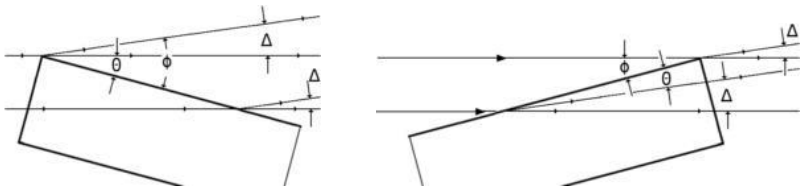
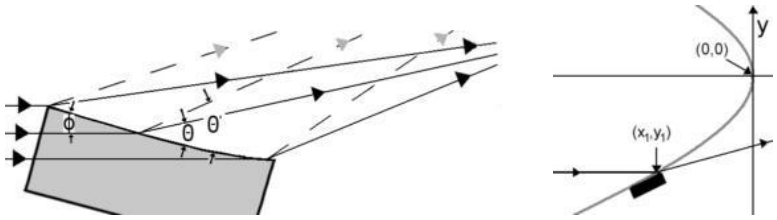
16.) **W. Jark,** *Comment on "Using compound kinoform hard X-ray-lenses to exceed the critical angle limit"*, Phys. Rev. Lett. **101**, 219501 (2008)
17.) D. Korytár, P. Vagovič, K. Végsö, P. Šiffalovič, E. Dobročka, **W. Jark**, V. Áč, Z. Zápražný, C. Ferrari, A. Cecilia, E. Hamann, P. Mikulík, T. Baumbach, M. Fiederle, M. Jergel, *Potential use of V-channel Ge(220) monochromators in X-ray metrology and imaging*, J. of Appl. Cryst., **46** (4), 945-952 (2013).

Phenomenon [2]: refraction of a plane X-ray wave at a flat interface



1.) W. Jark, L. Rigon, K. Oliver, *Simultaneous determination of the x-ray refractive index and the attenuation length from a single radiograph of rectangular prisms*, Opt. Commun. **284** (19), 4525-4528 (2011)

Phenomenon [3]: one-dimensional focusing of X-rays by refraction at a concave interface

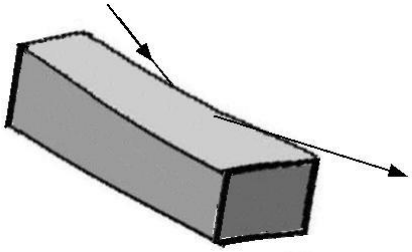


1.) **W. Jark**, L. Rigon, K. Oliver, *Revisiting the "forgotten" first zoomable refractive x-ray lens*, SPIE - Proceedings: Advances in X-ray/EUV Optics and Components VI. Vol. **8139**, 81390G (2011)

related to this chapter

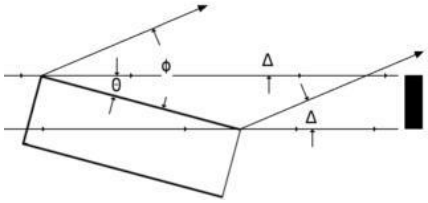
1.) **W. Jark**, *On the optimisation of the spectral resolution in spectrographs for cold neutrons based on refraction at grazing incidence*, Nucl. Instrum. Methods A **735,** 291-296 (2014).

Phenomenon [4]: two-dimensional focusing of X-rays by refraction in a curved edge



1.) **W. Jark**, G. Grenci, *Bi-dimensional focusing of X-rays by refraction in an edge*, Opt. Lett. **39**, 1250-1253 (2014)
2.) **W. Jark**, G. Grenci, *Focusing X-rays in two dimensions upon refraction in an inclined prism*, SPIE - Proceedings: Advances in X-ray/EUV Optics and Components IX, Vol. **9207**, 92070A (2014)

Phenomenon [5]: shadow behind an X-ray refracting short interface



1.) **W. Jark**, *Proposal for a source size and source position monitor for high power x-ray sources based on a "negative" pinhole camera*, SPIE - Proceedings: X-Ray Free-Electron Lasers: Beam Diagnostics, Beamline Instrumentation, and Applications II, Vol. **9210**, 92070L (2014)