Novel Micro-Pore X-ray Optics Produced with Micro-Channel Plate Technology

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Novel micro-pore X-ray optics produced with micro-channel plate technology

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ABSTRACT

A novel type of micro-pore optics for the X-ray regime has been developed. These optics have a radial design instead of the square packing in the more traditional Lobster-eye optics. With such a design true imaging, without a crucifix in the focus, can be achieved. We demonstrate that the walls inside the square pores are good enough to produce sub-arcminute focussing up to photon energies above 10 keV. The current performance of the optics is limited by large-scale distortions of the plates, probably caused by the method to fuse the fibers together.

Keywords: Micro-pore optics, micro-channel plates, X-ray optics

1. INTRODUCTION

Because X-rays can only be reflected efficiently at grazing incidence angles, the collecting area of an X-ray optic is much smaller than the total area of reflecting surfaces. This leads to large and heavy optics as compared to optics for visible light. The weight of the X-ray optics is roughly proportional to the thickness of the reflecting surfaces.

It has been demonstrated in the past that the weight and size of X-ray optics can be dramatically reduced with the technology that is used to produce micro-channel plates, which makes it possible to produce glass optics with reflecting surfaces that are only a few micrometer thick. Such optics consist of plates of a few millimeters thick which have millions of holes in them. Traditional types of such micro-pore optics have square holes in a square packing arrangement (Fig. 1), which leads to a Lobster-eye configuration. Photons that reflect from one surface are focussed into a line; the two orthogonal sets of walls lead to a crucifix focal spot. Only photons that reflect twice, from two orthogonal walls, are brought to a real focus. The angular resolution is limited both by the crucifix image, distortions of the walls of the pores and misalignment of the pores. Resolutions down to a few arcminutes have been obtained in the past.³

We have produced and evaluated prototypes of a novel type of micro-pore optic that produces a true focus. Instead of a square arrangement, the fibers are stacked radially (Fig. 2). The wall surfaces resemble a nested set of cylindrical shells such as used in the Wolter-I optics traditionally used for X-ray optics, albeit with very thin walls. One such plate would suffer however from severe coma for an off-axis source. With two plates, curved to the right curvature, a classical Wolter-I geometry is obtained, in which the coma is counterbalanced and a true imaging optic is obtained (Fig. 3).

Preliminary results obtained with such plates were reported earlier.² In this report we show that we have been able to produce fibers and multifibers of sufficient quality to achieve sub-arcminute angular resolution. We show measurements of the surface roughness and reflection coefficients at X-ray energies that were performed to evaluate whether the surfaces are of sufficient quality to reflect X-rays at higher energies. Measurements of the imaging properties of a single radial plate show that sub-arcminute angular resolution can be obtained, provided that large-scale distortions ('warp') can be eliminated.

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Figure 1. Square fibers in a square packing arrangement. The size of the pores is $10 \times 10 \mu\text{m}^2$.

Figure 2. A radially packed micro-pore optic. Individual multifibers of about $0.7 \times 0.7 \text{ mm}^2$ are stacked in circles around a core cylinder. Each multifiber contains 55×55 fibers.

Figure 3. A possible arrangement of micro-pore optics that would mimic a Wolter-I optic. A true Wolter-I optic would have a parabolic and hyperbolic section with focal lengths that differ by a factor of three. The micro-pore optic implementation has flat walls; the plates are slumped to radii that differ by a factor of three.

Measurements were performed with synchrotron radiation up to 10 keV at the four-crystal monochromator beamline of the Physikalisch-Technische Bundesanstalt at BESSY II, and above 10 keV at the optics beamline BM5 at ESRF. Full-illumination measurements were performed with the 20 m beamline facility at Leicester University.

2. MICRO-PORE OPTICS PRODUCED WITH MICRO-CHANNEL PLATES

The micro-pore optics that we describe in this report were produced with the technology that is used for micro-channel plate detectors. The process starts with a block of glass of about $10 \times 10 \times 50 \text{ cm}^3$, which consists of a core and a cladding of a different type of glass. To obtain square pores a square core and cladding are used. The surface of the core is polished to optical quality. In a fiber drawing tower a fiber is drawn from this block, with a size of about $0.5 \times 0.5 \text{ mm}^2$. Pieces of 30 cm length are stacked in a square geometry of 55×55 fibers. This is then also drawn in the drawing tower, after which multifibers of about $0.7 \times 0.7 \text{ mm}^2$ are obtained. The size of individual fibers in this multifiber is now reduced to $12 \times 12 \text{ }\mu\text{m}^2$.

Segments of multifibers of 60 mm length are assembled in the desired radial configuration and fused at an elevated temperature. From the resulting boule plates of a few mm thickness are cut and polished.

In the final step the plates are etched. The glass of the cladding is not attacked by the etching fluid, whereas the core glass is etched away after a few days, leaving behind a grid of walls that are $2 \text{ }\mu\text{m}$ thick and that form long square channels with an aspect ratio of 200:1 to 500:1, depending on the thickness of the plate.

3. PERFORMANCE OF INDIVIDUAL FIBERS

From Fig. 1 it can be seen that individual fibers have at first sight square corners and flat walls, and no other apparent defects are visible. This is also confirmed by X-ray reflection measurements performed with a $10 \text{ }\mu\text{m}$ diameter beam. Some walls produce a reflected spot whose width corresponds to less than 10 arcsec, whereas most are below 1 arcmin.

From the reflectivity as a function of energy for a few incident angles the following was deduced:

- the cut-off energy indicates that the density of high-Z atoms in the surface, the main contributors to the reflectivity, is lower than that of the bulk glass. The theoretical curves correspond to a density of 0.3 times that of the bulk glass.
- the fact that the reflectivity does not decrease below the critical energy indicates that the surface roughness is below 15 ÅRMS.

The surface roughness was also measured with a phase microscope.¹ Fig. 4 shows the power spectral density of the surface roughness as a function of spatial wavelength. The RMS surface roughness over the measured band of spatial frequencies varied between 5 and 15 Å for most fibers. Note that there is a systematic difference between the sides of the walls. This effect was also observed in the X-ray measurements on some of the samples. It is most likely related to the orientation of the plates during etching. The origin of the periodicity that causes the peaks in the spectra is unknown.

4. MULTIFIBER PERFORMANCE

Individual multifibers, which consist of 55×55 fibers, have been measured at X-ray energies. To this end multifibers were cemented together and polished and etched, after which the cement is dissolved. The remaining multifiber segments are 5 mm long. Fig. 5 shows the spot that is reflected from such a fiber at an incident angle of 0.05 deg. Some multifibers have an image quality between 20 and 50 arcsec, other multifibers produce reflected spots that are between 1 and 2 arcmin wide. The cause for this difference is not yet understood.

5. PLATE PERFORMANCE

When a radially packed plate such as depicted in Fig. 2 is illuminated with X-rays from a source at a finite distance, a focus is obtained at the same distance behind the plate (Fig. 6).

Fig. 7 shows the image that results from illumination with a strip of $30 \times 3 \text{ mm}^2$ with a source distance of 25 m. There are a few separate contributions to this image:

- the small bright spots around the center are caused by the holes between the multifibers,
- the bright spots at the sides are caused by direct transmission through the pores,

Figure 4. The power-spectral density of the surface roughness inside the pores in the plate.

f

f

Figure 5. The spot reflected off a multifiber at 10 keV. The FWHM is 20 arcsec. Good multifibers have a FWHM between 20 and 50 arcsec, most multifibers have a FWHM of about 1.5 arcmin. (PTB-Bessy)

Figure 6. A flat radially packed plate will image an on-axis source. The image distance is equal to the source distance.

Figure 7. The image produced by illuminating a radially packed plate with a $30 \times 3 \text{ mm}^2$ wide beam with a source distance of 25 m and an energy of 10 keV. The small bright spots are caused by transmission through the triangular holes between the multifibers. The large spots at the sides are caused by transmission through the pores. The central elliptical spot is the true focus of the plate; its half-energy width corresponds to an angle of 2 arcmin. (ESRF)

- the central spot is the focus of properly reflected rays.

The fact that no transmission through the pores is seen close to the center indicates that the fibers are misaligned close to the center. Measurements of the fiber alignment confirm that the fibers are tilted radially close to the center, as though the plate was deformed into a 'nozzle' shape. This is most likely caused by a mismatch of the thermal expansion coefficient of the central glass cylinder.

Fig. 8 shows the focus of a radially packed plate when illuminated with mostly 8.4 keV radiation from a source at a distance of 10 keV. The fact that only the outer ring transmits is again caused by the 'nozzle' shape of this plate. The focus produced by the outer ring has a FWHM of 1.1 arcmin, which is well below the best result achieved so far with square-pore, square-pack optics. The corresponding effective collecting area is currently limited to only a few square mm.

Figure 8. The image that is produced at a distance of 10 m behind a radially packed micro-pore optic that is illuminated with mostly 8.4 keV radiation from a source at 10 m distance in front of the plate. The FWHM of the spot in the center is 1.1. arcmin. (Leicester University)

The image quality is limited by large-scale distortions of the plate, that is with a low spatial frequency ('warp'). This effect is removed in Fig. 9, which shows the result of overlaying 36 strip measurements as shown in Fig. 7, but each time rotating the plate over 10 deg so that the total plate is illuminated in 36 measurements. Because the plate was realigned for each strip, the lowest order distortions of the plate are effectively removed. The result is a good indication of the quality of the plate that would be achieved when the lowest order distortions are removed. FWHM of the central spot is 18 arcsec, the half-energy width is 36 arcsec.

Figure 9. The image quality of the radially packed plate constructed from 36 strip illuminations of the plate, so that effectively the lowest order distortions are removed. One pixel corresponds to an angle of 0.9 arcsec. (ESRF)

6. CONCLUSION AND OUTLOOK

The use of micro-channel plate technology to produce radially packed micro-pore X-ray optics looks very promising. The quality of individual fibers is good enough to reflect X-rays up to 20 keV and to obtain an image quality of better than 20 arcsec.

The quality of multifibers varies, but selected multifibers produce a spot of less than 20 arcsec wide.

It has been possible to produce plates that are radially packed, and therefore do not produce a crucifix image but when used as a Wolter pair produce a true focus. An image quality of 1.1 arcmin was demonstrated, albeit with a small effective area. When the 'warp' of the plates can be eliminated the image quality would become about 36 arcsec HEW. The effective area is limited by radial tilt of the fibers, which is most likely caused by the core cylinder used to stack the plates.

The next step is to slump the plates into a spherical shape, so that a true Wolter optic can be produced. The results presented here indicate that such an optic could provide a competitive image quality at very low mass.

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