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High-resolution micro-pore X-ray optics produced with micro-channel plate technology

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ABSTRACT

Using the technology that has been developed over many years for the fabrication of glass micro-channel plates, a prototype micro-pore optic has been produced that is a very light and compact implementation of a Wolter-I optic for X-ray imaging. With this prototype true Wolter-I imaging has been observed for the first time in a micro-pore optic. Individual fibers in the plates are found to be quite good, with a surface roughness permitting application at medium X-ray energies. The image quality and effective area is however seriously reduced by random tilt errors of multifibers in the plates. If this limitation can be overcome, this technology would allow very light and compact X-ray telescopes to be built. A design is presented that already provides a considerable effective area for soft X-rays using the properties of the surfaces obtained in this program.

Keywords: X-ray optics, Micro-channel plates, Micro-pore optics, X-ray astrophysics, X-ray telescopes

1. INTRODUCTION

The technology used to produce glass micro-channel plates offers the possibility to develop X-ray optics with very thin reflecting surfaces, of the order of a few micrometers. This results in far lighter and smaller optics than would be possible with conventional grazing incidence optics. The use of this technology to produce an X-ray focusing optic has been previously demonstrated, however based on square fibers packed in a square geometry.^{1,2} Such a Lobster-eye optic produces a crucifix image, which limits the imaging quality.

We are developing optics with this square packed geometry and improved geometries that should lead to ultra-light X-ray optics with competitive image quality.^{2,3} We have been able to improve considerably the quality of the optics in which the fibers are arranged in a rectangular grid. The figure quality of individual fibers translates into a focal spot with a half-energy width of 20 arc seconds at 3 keV. The RMS surface roughness, as determined from the X-ray reflectivity and surface roughness measurements, is below 15 Angstrom. The image quality of a 50x50 mm optic has resulted in an HEW of a few arc minutes, which is currently limited by large-scale distortions of the plate.

We have also produced the first prototype of an optic in which the fibers are packed radially. Such an arrangement is essentially a conical approximation to a Wolter-I design and removes the crucifix shape from the focal image produced by an optic that is arranged in the traditional square packed arrangement. With a single prototype plate we have achieved an image quality over large sectors of the plate of about 1 arc minute half-energy width. This optic is therefore already useful as an X-ray concentrator. Two of these plates used in tandem and slumped to a spherical profile would act as a Wolter-I type X-ray optic with true imaging capabilities. The final goal of the program was to produce a prototype of such a tandem pair. In this paper we present the results that we have obtained in producing these micro-pore optics. The report will include metrology performed on the plates, their X-ray performance as measured in X-ray test facilities, and possible designs for an X-ray astronomical telescope based on this technology.

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Figure 1. A tandem of two radially packed micro-pore optics, each 60 mm in diameter and 5 mm thick. One plate is slumped to a radius of curvature of 20 m, the other to 6.67 m. The pair constitutes a thin and light Wolter-I optic.

2. MICRO-PORE OPTICS FROM MICRO-CHANNEL PLATES

The micro-pore optics described here are produced with the technology that is used for micro-channel plates. However, instead of a boule consisting of a cylinder of core glass with a cylindrical cladding, a square boule with a square cladding is used, which measures about $50 \times 50 \text{ mm}^2$. In a drawing tower, this boule is drawn to a square fiber of about $0.5 \times 0.5 \text{ mm}^2$. These fibers are stacked in a square arrangement of 55×55 fibers, and drawn again to a square fiber, a so-called multifiber, of about $0.7 \times 0.7 \text{ mm}^2$. These multifibers are stacked in concentric circles to become a cylindrical block of 60 mm diameter. This block is fused at an elevated temperature, and then cut into slices that are 5 mm thick. These slices are polished and then slumped to a spherical shape between a pair of matched spherical surfaces, at an elevated temperature. The plate is then submerged in etching fluid that removes the square cores of the fibers, leaving behind the cladding glass. The result is a 5 mm thick plate of 60 mm diameter, that has about $2 \cdot 10^7$ square holes of $10 \times 10 \text{ } \mu\text{m}^2$ at a pitch of $12 \text{ } \mu\text{m}$. The walls between the pores are $2 \text{ } \mu\text{m}$ thick. The walls that face the radial axis of the plate form a set of conical surfaces centered on the plate axis.

When such a plate is used to focus X-rays from an on-axis source, either at infinite or finite source distance, the reflections from these walls will produce a sharp focus. For an off-axis source, however, the image will suffer from extreme coma.

We have produced a tandem pair of these plates, one slumped to a radius of curvature of 20 m and one to a radius of curvature of 6.67 m (Fig. 1). This configuration approximates a classical Wolter-I optic, where a reflection from a parabolic surface is followed by a reflection from a hyperbolic surface. The second reflection balances the coma from the first reflection, so that a true imaging optic is obtained. The fact that the reflecting surfaces are not curved, as is the case in a Wolter-I design, is only a small effect given that the thickness of the plates and therefore the length of the reflecting walls is very small compared to the focal length.

3. FIBER QUALITY

As reported before, the image quality of individual fibers, as measured with a $10 \text{ } \mu\text{m}$ pencil beam in the PTB laboratory at the BESSY II synchrotron facility, is for a large fraction of the fibers around 20 arcsec, but for another large fraction between 1 and 2 arcmin.³ There seems to be a difference between differently oriented walls in the plates, but the systematics are not yet understood.

From measurements of the reflectivity as a function of energy and incident angle it is concluded that the density of heavy elements (Pb, Bi) in the surface is reduced as compared to the composition of the bulk cladding glass, by a factor of 2.5. This is confirmed by composition analysis of the glass. The variation in the reduction of heavy elements depends on the details of the etching process, and can probably be minimized.

No scattering losses could be observed, which is only possible if the RMS surface roughness is below $15 \text{ } \text{\AA}$. This is confirmed by direct optical metrology of the surfaces using a phase microscope. Such measurements on several fibers in a typical sample gave an RMS surface roughness of 3 to $18 \text{ } \text{\AA}$, with an average of $9 \text{ } \text{\AA}$, in the spatial frequency band of 1 to 1000 mm^{-1} .

4. SINGLE PLATE IMAGING QUALITY

The orientation of single fibers within a multifiber is better than the image quality of individual fibers. Measurements of the orientation of the multifibers in a single slumped plate show that the fibers are on average tilted according to the radius of curvature of slumping, but besides that they also exhibit random tilt errors of about 0.05 deg. These random tilt errors are larger than the tilts induced by the 20 m radius of curvature of one of the plates. From measurements that only illuminate part of the plate at any time it is estimated that the on-axis focus of a single plate, when used as a X-ray collector, has a FWHM well below an arcmin with an effective area of about 30 mm². The effective area is considerably less than expected for an undistorted optic, which is caused by the considerable random tilt errors of the multifibers.

5. WOLTER PAIR IMAGING QUALITY

The quality of the combined pair of plates, which mimics a Wolter-I configuration, has been evaluated with monochrome 10 keV radiation at the European Synchrotron Radiation Facility. A beam of 60×3 mm² with a source distance of 53 m illuminates a cord line of the plate. As a detector a fluorescent screen is used that is placed at a distance of 5.3 m, close to the expected focus. The image on the fluorescent screen is imaged with a CCD camera.

In the image radial lines are visible that correspond to reflections from the plates that produce a streak through the focus (Fig. 2). The orientation and figure of the fibers are sufficiently accurate to center the streak on the optical axis. When the optic is tilted, this streak does not move, as is the case for an image behind a normal positive lens in the optical regime. This is the first observation of true Wolter-I-type focusing by a micro-pore optic.

The images also show transmission and spots caused by an even number of reflections inside the pores, which show as bright lines at the position of the incident beam. There is also an off-axis diffuse spot, which moves when the optic is tilted. This spot is the extra-focal image of single reflections from the second plate. This can occur for radiation that passes through the first plate because the pores in this plate do not completely intercept the incident radiation, or for radiation that reflects an even number of times in the pores of the first plate.

As can be seen from the images, only a small part of the plates contributes to the normal focus. This is caused by the random tilt errors in the multifibers. When the plate is tilted, different parts of the plate contribute to the focus. The estimated effective area with the strip illumination is of the order of a square mm, which would correspond to an effective area of less than a square cm for the entire optic. Furthermore the image and the effective area will depend heavily upon the orientation of the source in the field of view.

Thus the main issue identified in this program is the random tilt error of multifibers. This could be improved either by optimizing the current production process, or by controlled assembly of individual multifibers.

6. APPLICATIONS

Provided that the random tilts between multifibers can be reduced, the X-ray optics produced with this technology would allow to make light and thin optics. This is not only useful for a hard-X-ray telescope, but would also provide advantages for a soft-X-ray telescope. As an example we have evaluated possible designs for a compact soft X-ray telescope (up to 2 keV) with a focal length of 0.9 m. For this soft X-ray application we choose a design pore size of 50×50 μm² with an open area ratio of 65%.

Let us first assume that the aspect ratio will be low enough to coat the surface of the pores on the inside with gold. The reflectivity of gold for 1 keV radiation drops rapidly beyond 3.5 deg, which limits the useful diameter at 1 keV to 0.44 m. It might prove to be too difficult to produce single-piece plates of this diameter, in which case the optic can be assembled from smaller modules. The surface utility (effective collecting area per unit area of wall surface) at 1 keV radiation is above 50% of its maximum at 1.7 deg between 0.6 and 3.0 deg. At 2 keV, the surface utility is above 50% of its maximum at 1.2 deg between 0.4 and 1.8 deg.

These angles correspond to a plate thickness between 1 and 7 mm. At a thickness of 3.6 mm a reasonable balance between the collecting area at 1 keV and 2 keV is found, which are 178 and 78 cm² respectively, at a weight of only 1.0 kg of glass. The effective area can therefore be up to 178 cm²/kg at 1 keV. Even if only 50% of this area can be achieved in practice, it is still 30 times larger than the same numbers for traditional X-ray telescopes; ESA's XMM-Newton X-ray telescope is one of the more efficient ones at 3 cm²/kg at 1 keV. The large difference is directly

Figure 2. The image produced by illuminating a strip of the tandem of two slumped micro-pore plates with 10 keV synchrotron radiation at ESRF. The rectangle indicates the illuminated area, the cross mark indicates the optical axis. a) Visible in the image is transmission/even number of reflections through the optic (curves), and properly focussed double reflections from a small part of the plate (streaks through the optical axis). These images do not move when the optic is tilted. b) Illuminated along a different line, the image shows also single reflections from the second plate (diffuse spot in lower right corner). This spot moves when the plate is tilted.

caused by the ratio of the wall thickness. It is the rigidity of the structure of the micro-pore optics that allows us to use such thin walls.

Due to the uniform thickness of the plates, this design also suffers from more background and optical and X-ray stray light than a closely packed and properly baffled Wolter-I nest, such as the XMM and Chandra optics. This is partly caused by the fact that the pore size is uniform, so that pores that are close to the optical axis do not fully intercept the incident radiation. Furthermore, the fact that reflections from the four walls of the pores are equally efficient improves on the one hand the efficiency, as an odd number of reflections inside a pore comes out in the same direction as one reflection. But at the same time it increases visible and X-ray stray light. These effects can be reduced or eliminated by varying the plate thickness or pore diameter as a function of distance to the optical axis. Alternatively the optic could be built as a thin annulus, thereby trading bandwidth for image quality.

Such optimization would also increase the effective area. The gain in effective area per unit weight could then approach the ratio of the wall thickness in these plates versus the thickness of traditional shells, which is 250 or more.

If we would use the glass surfaces as produced in this program without coating, the reduced density of heavy elements at the surface reduces the effective area that can be achieved. The surface of these samples only contribute significantly between 0.4 and 1.4 deg at 1 keV, and between 0.25 and 0.75 deg at 2 keV. For the material produced in this program, a plate with a thickness of 7 mm and a diameter of 0.2 m would provide an effective area of 64 and 10 cm² at 1 and 2 keV respectively, and contain 0.4 kg of glass. To obtain the same collecting area with traditional shell optics would however require of the order of 20 kg of optics.

7. CONCLUSION

We have produced a light and very compact prototype Wolter-I optic using a modification of the technology used to fabricate micro-channel plates. For the first time proper Wolter-I-type imaging has been observed from a micro-pore optic.

The imaging quality of individual fibers and of multifibers is found to be quite good, at 20 arcsec FWHM for a large fraction of the fibers.

The main problem that was identified is the fact that the multifibers exhibit random tilt errors of about 0.05 deg. This is most likely caused by the method that is used to stack the multifibers into concentric rings. This could be improved by optimizing the stacking procedure. Alternatively an optic could be effectively grown by the controlled assembly of multifibers, using a metrology system so that the multifibers are properly oriented for focusing.

The surface roughness that was observed in this program is considerably lower than what has been observed before. This makes the application of such optics at higher energies (above 20 keV) feasible, provided that the density of heavy elements in the surface can be improved, for example by optimizing the etching process or coating the surface of the pores.

An interesting result obtained during the program is that the surface roughness of a single-draw fiber, that is before the initial fibers of about $0.5 \times 0.5 \text{ mm}^2$ are drawn again to become multifibers, is also low enough so that no scattering losses could be observed up to 25 keV, which indicates a surface roughness below 15 Å. This means that it is not necessary to draw the initial boule to a linear expansion ratio of a few thousand, as is the case after the second draw; a ratio of about 100 is apparently sufficient.

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