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Study of the optical properties of a square polycapillary slice

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ABSTRACT

Conventional polycapillary X-ray lenses, which are important components of widely used X-ray optics, are very suitable for focusing or parallelling the X-rays. However, for the hexagonal arrangement of the capillary, there are some shortcomings when it is used for X-ray imaging. Although, these shortcomings can be overcome by adopting a polycapillary X-ray lens structure with a square cross-section fabricated from a square matrix array of capillaries, it is challenging to manufacture it. In this paper, we present a new type of X-ray optics: a square polycapillary slice, which is 3 mm thick. It is like a sheet and consists of 1080×1080 square arrayed square micro-channels. Each external wall of a square micro-channel can be approximately expressed as a paraboloid. To study its optical properties, we conducted both simulation and experimental measurements. The simulated results showed that the focal distances of the cases in which the square polycapillary slice had no fluctuations and had fluctuations were 36.7 ± 0.9 and 36.7 ± 1.8 mm, respectively. The measured focal distance was 36.6 ± 2.5 mm. The full widths of the simulated focal spot of the cases in which the square polycapillary slice had no fluctuations and had fluctuations were 621 and 657 μm, respectively. The full width of the measured focal spot was 600 μm. The centre area of the focal spot was star-like. Its optical properties were similar to those of the polycapillary X-ray lens. Because the micro-channels are squared arrayed, it is more suitable for X-ray imaging than conventional polycapillary X-ray lens.

1. Introduction

X-ray is a type of high-energy and short wavelength electromagnetic wave. The optical properties of X-rays are different from visible light, and optical devices for visible light are not suitable for X-rays. In past studies, a variety of X-ray optical devices, such as the Kirkpatrick–Baez (KB) mirror [1], Bragg mirror [2], multilayer film reflector [3], X-ray zone plate [4], compound refractive lenses [5], capillary optics [6], and lobster eye X-ray optics [7], have been developed. Among them, capillary optics is the most widely concerned X-ray optical device.

Capillary optics is a capillary system that uses the principle of total external reflection to transmit X-rays. Based on the different structures of capillary optics, they are divided into single capillary X-ray optics and polycapillary X-ray lenses. The polycapillary X-ray lens consists of hundreds of thousands of capillaries, and each capillary tube has a different contour curve equation. It is very suitable for focusing or parallelling X-rays. In past studies, it has been widely applied to X-ray fluorescence analysis, X-ray diffraction analysis, EXAFS experiments, etc [8–11]. Besides, Korecki et al. [12,13] applied it for coded aperture imaging. Because of the hexagonal arrangement of the capillary, there are some shortcomings when it was used for X-ray imaging. This arrangement necessarily includes triangular-shaped non-functional spaces between the capillaries. These non-functional spaces reduce the transmission efficiency of the lens and can also affect the utilisation of the pixels of charge-coupled devices in imaging applications [14]. One simple approach to rectify these disadvantages is to adopt a polycapillary X-ray lens structure with a square cross section fabricated from a square matrix array of capillaries, each with equivalent square cross sections. In previous studies, a model of this type of capillary lens has been proposed [15] and a simulation work [14] has been completed. However, it is challenging to manufacture it.

In the present paper, a new type of X-ray optic is proposed: a square polycapillary slice. It is like a sheet and consists of 1080×1080 square arrayed square micro-channels, where each external wall of the square micro-channels can be approximately expressed as a paraboloid. To study its optical properties, we conducted a simulation based on a ray-tracing method and experimental measurements.

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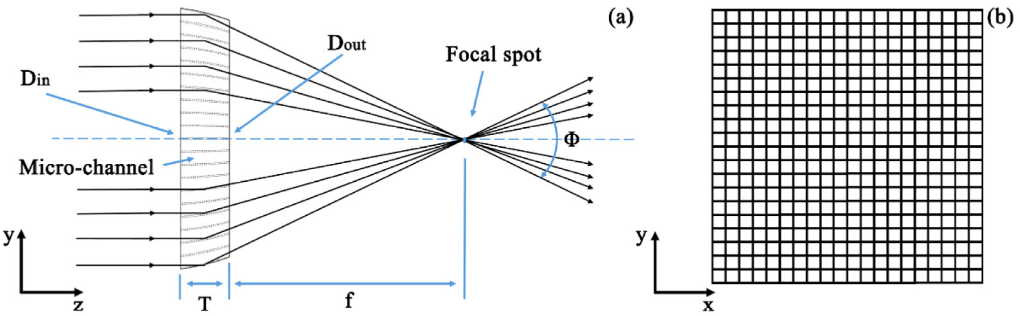

Fig. 1. (a) Schematic representation and (b) cross-section of the square polycapillary slice.

2. Model and experimental

2.1. Model of the square polycapillary slice

If the X-rays are incident on the inside wall of a glass capillary at an angle θ that is less than the critical angle for total reflection, the X-rays will be reflected [16]. While reflection changes the direction of X-ray propagation, the X-ray will be focused when it is transmitted by the square polycapillary slice if the tangents to the edges of all square channels point towards a fixed point on the central axis, as illustrated by the schematic given in Fig. 1(a). Based on this principle, a square polycapillary slice consisting of 1080 × 1080 square micro-channels was designed. Each external wall of the square micro-channel can be approximately expressed as paraboloid. The cross-section of the square polycapillary slice is a square, and the cross-section of each capillary is also square, as shown in Fig. 1(b).

2.2. Manufacturing of the square polycapillary slice

As shown in Fig. 2(a), the manufacturing process of the square polycapillary slice consisted of a drawing process, array process, slicing process, and corroding process. First, a square core rod with a smooth surface would was processed. Its outer diameter was slightly smaller than the inner diameter of the square cladding. Then, the core rod was filled into a square cladding, which was made of borosilicate glass, to manufacture the square bar. By drawing the square bar with a drawbench, we were able to manufacture a square fibre with a length of 40 cm. In this process, the square bar was heated to 700–750 °C. After that, numerous square fibres were arranged in a square-fibre bar and the square multi-fibre was drawn. The square fibre and the square multi-fibre were shown in Fig. 2(b). In a similar way, square multi-fibres were arranged in a multi-fibre bar and a solid square cone was drawn, as shown in Fig. 2(c). Each external wall of the solid square cone can be approximately expressed as a paraboloid. To obtain the square polycapillary slice, we first cut the square cone into a set of 3-mm-thick solid slices. After sanding its surface, we applied a corrosion technology to the solid slice. The core material was eroded away, and the square polycapillary slice was manufactured.

To study its optical property, a square polycapillary slice was used for the measurements. Its picture and microscope images were shown in Fig. 2(d) and (e) respectively. The shape curve on its centre axis direction was a quadratic curve, as shown in Fig. 2(f). There were some fluctuations in the curve shape. The major parameters of the slice were given in Table 1.

2.3. Experimental measurement

Fig. 3(a) shows the schematic diagram of the experimental arrangement. The polycapillary parallel X-ray lens (PPXRL) is used to obtain parallel X-ray beams. Fig. 3(b) shows a photograph of the experimental setup. An X-ray tube with a Cu target [MCBM 50-0.6B, RTW, Germany] was operated at 15 kV and 0.1 mA. The focal spot size of the X-ray tube was 50 μm. The PPXRL was placed near the X-ray tube, and it was designed and manufactured by the College of Nuclear Science and Technology of Beijing Normal University. The input focal distance was 50.5 mm at an X-ray energy of 8.04 keV (Cu Ka), and the outlet size was 16 mm. An X-ray imaging system [M11427-61, Hamamatsu, Japan] was used to detect the spot of the square polycapillary slice. The resolution of the X-ray imaging system was 10 μm.

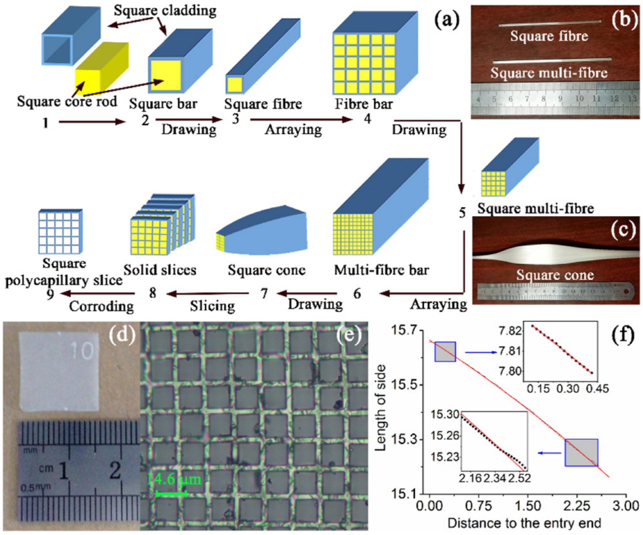

Fig. 2. (a) Manufacturing process of the square polycapillary slice; (b) Square fibre and square multi-fibre; (c) Square cone; (d) Picture of the square polycapillary slice; (e) Microphotograph of the square polycapillary slice; (f) Scanning curve of the square polycapillary slice on its centre axis direction.

3. Results and discussion

In this work, a simulation program [15,17] based on a ray-tracing method was used to study the optical properties of the square polycapillary slice. Since the parallel X-ray beams obtained by the polycapillary parallel X-ray lens exhibited a Gaussian distribution of intensity, the simulated X-ray source was also a Gaussian-distributed planar source, which emitted a parallel beam and had an energy of 8.04 keV.

Fig. 4 shows the measured and two simulated intensity change curves at different positions. The maximum intensity position of the measured intensity was 36.6 mm. The maximum intensity positions of the two simulated intensities were both 36.7 mm. Considering the uncertainty of the fitting, we expressed the measured maximum intensity positions as 36.6 ± 2.5 mm, i.e., the measured focal distance of the square polycapillary slice was 36.6 ± 2.5 mm. In the same way, the simulated focal distances of the cases in which the square polycapillary slice had no fluctuations and had fluctuations were expressed as 36.7 ± 0.9