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Hard X-ray imaging by a spherical compound refractive lens

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ABSTRACT

Hard X-ray imaging by a spherical compound refractive lens is presented. The lens is composed of 123 biconcave microlenses with a size of 200 μm in diameter. Each microlens was formed by the epoxy between two bubbles, which were injected into an epoxy-filled glass capillary. The focal length of the lens is 114 mm at 8.05 keV. The light source was obtained by using a copper anode X-ray tube without a filter. The lens can be achieved a spatial resolution of 5 μm with field of view of about 700 μm , and 1–3 μm resolution may be obtainable by using monochromator and diaphragm.

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1. Introduction

There is a growing demand for non-destructive hard X-ray microscopy techniques to visualize the interior of opaque samples. Fresnel zone plates [1], and reflective optics [2] such as K-B systems, were used to form images, but these devices are generally expensive so that limit their applications in imaging systems. In addition, it is challenging to place and align them properly in practice. Almost all laboratory imaging was achieved by simple shadow casting from a microspot X-ray source. These apparatus, which are cheaper and easy to be aligned setup, can reach a resolution slightly below 1 μm . But their resolution is limited by the inherent resolution of the 2D detector, which is determined by the interaction of X-rays with a scintillator and the resolution of the visible light optics of the detector. Thus it is difficult to further enhancing resolution by using these types of microscopes [3]. Compound refractive lens (CRL), invented 12 years ago in European Synchrotron Radiation Facility (ESRF) [4], was used in hard X-ray collimating [5], nanofocusing [6,7] and imaging [8–11]. Due to its compact structure, flexible alignment, advanced technique of manufacture and large numbers of available materials, CRL could be used to focus hard X-rays in the range of 5–150 keV [12,13] or to image opaque samples illuminated by monochromatic X-rays, providing the resolution about 300–500 nm [9,11].

A spherical compound refractive lens consists of a series of bubbles encased in an epoxy-filled glass capillary, where the epoxy between two bubbles forms a biconcave spherical lens

under the action of surface tension forces [14,15]. There are three advantages ensuring good image quality of the lens for using in hard X-rays: (1) The epoxy ($\text{C}_{100}\text{H}_{200}\text{O}_{20}\text{N}$, 1.08 g/cm^3) is composed of carbon, hydrogen, and nitrogen, each of them is characterized by a low absorption coefficient for 5–30 keV X-rays. (2) Because of the nature of physics forming the bubble, the lens surface quality is extremely good. (3) The capillary ensures that the series of unit lenses are well aligned coaxially.

In this paper, images using an unfiltered X-ray tube and a spherical compound refractive lens were obtained, and resolution below 5 μm was achieved by using this apparatus.

2. Theory of compound refractive lens

The refractive index for X-rays in matter can be written as

$$n = 1 - \delta + i\beta \quad (1)$$

where δ is the refractive index decrement (typically between 10^{-5} and 10^{-7}) and β is the absorption index.

As shown in Fig. 1, each biconcave lens has a focal length of $f_1 = R/2\delta$. Due to the rather small refraction, the focal length is very large with a value of about 13 m in this lens. Based on the compound construction, a series of N biconcave unit lenses can be aligned in a line to form a CRL with total focal length f as:

$$f = \frac{f_1}{N} = \frac{R}{2N\delta} \quad (2)$$

where R is the radius of lens, which is equal to the radius of capillary [4].

Although the focal length formula is based on the thin-lens approximation, still the thickness of CRL are comparable to its

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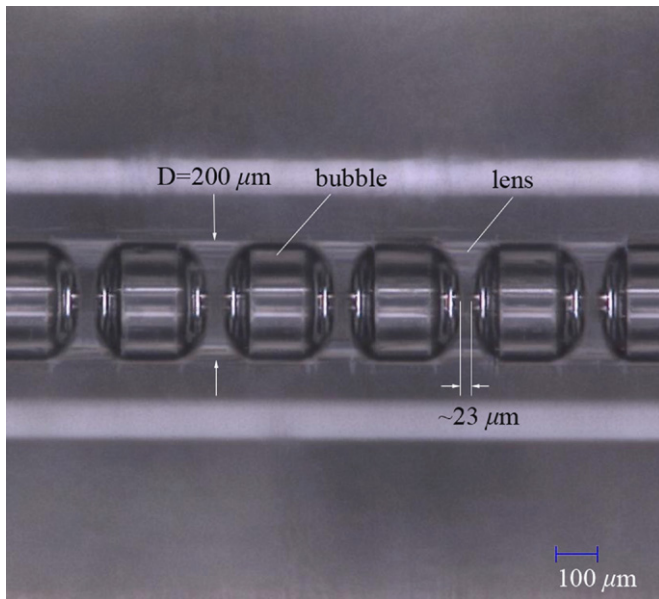


Fig. 1. Photograph of a spherical CRL inside glass capillary of 200 μm internal diameter. The interface between two air bubbles has a biconcave form and acts as a lens for X-rays. The average minimum thickness between two bubbles is 23 μm.

focal length, thus the thick-lens analysis must be used [16]. The focal length f_t of a thick lens can be formulated as

$$f_t = f \frac{(t/f)^{1/2}}{\sin(t/f)^{1/2}} \quad (3)$$

where t is the length of all lenses. The focal length f_t is measured from the principal plane of image space of a lens to the focal spot. The familiar lens formula can be rewritten as

$$\frac{1}{p} + \frac{1}{q} = \frac{1}{f_t} \quad (4)$$

where p is the distance from the object to the principal plane of object space of a thick lens, q is the distance from the principal plane of image space of a thick lens to image plane (sensitive plane of the X-ray camera). The magnification is given by the ratio $M = q/p$. The distance d between the lens surfaces and the principal plane can be calculated by [16]

$$d = f_t \left[1 - \cos\left(\frac{t}{f}\right)^{1/2} \right] \quad (5)$$

Due to the high absorption at the edges of the lens, the geometrical aperture is much larger than the effective aperture D_{eff} , which is defined as the opening diameter where the image intensity has decreased to e^{-2} of its peak value.

$$D_{eff} = 4 \left(\frac{\delta f_t}{\mu} \right)^{1/2} \quad (6)$$

where μ is the linear absorption coefficient of lens material [4]. The effective aperture D_{eff} can be used to determine some important parameters of the lens such as the field of view (FOV), which can be expressed as [10]

$$FOV = \frac{2D_{eff}p}{t} \quad (7)$$

3. Expected resolution

The spherical CRL is composed of 123-unit spherical and biconcave microlenses, and each of the microlenses can be

deemed as an optical element with the curvature radius of 100 μm in this experiment. The total length of the lens t is 41 mm. The spherical CRL was fabricated by injecting air bubbles into the epoxy-filled capillary one by one [17]. For 8.05 keV monochromatic X-rays, the refractive index decrement δ is 3.781×10^{-6} calculated by the formula of $\delta = 0.5(22/E)^2$, where E is photon energy measured in electron volts [18]. The linear absorption coefficient of lens material μ of the epoxy is 5.8 cm^{-1} in this experiment. The focal length f_t , according to Eq. (3), is 114 mm. The effective aperture D_{eff} is equal to 109 μm. The distance d from the lens surfaces to the principal plane is 21 mm. The distance between the center of the lens and the lens surfaces is 20.5 mm, and the principal plane is 0.5 mm away from the center of the lens.

The imaging was simulated by the commercial program of ZEMAX [19]. The optical model was built exactly the same as the design. Considering the source was an unfiltered X-ray tube, polychromatic light was used, which consisted of 7, 8.05 and 8.98 keV X-rays. Mesh #1500 (5.5 μm wires separated by 16.5 μm) was set as object and was placed at a distance of $p = 133 \text{ mm}$ from the principal plane of object space of the lens. The image plane was put at $q = 798 \text{ mm}$ behind the principal plane of image space of the lens with a magnification of $M = 6$. Geometric image analysis and MTF were performed. As can be seen in Fig. 2, the image was not satisfactory when light source is

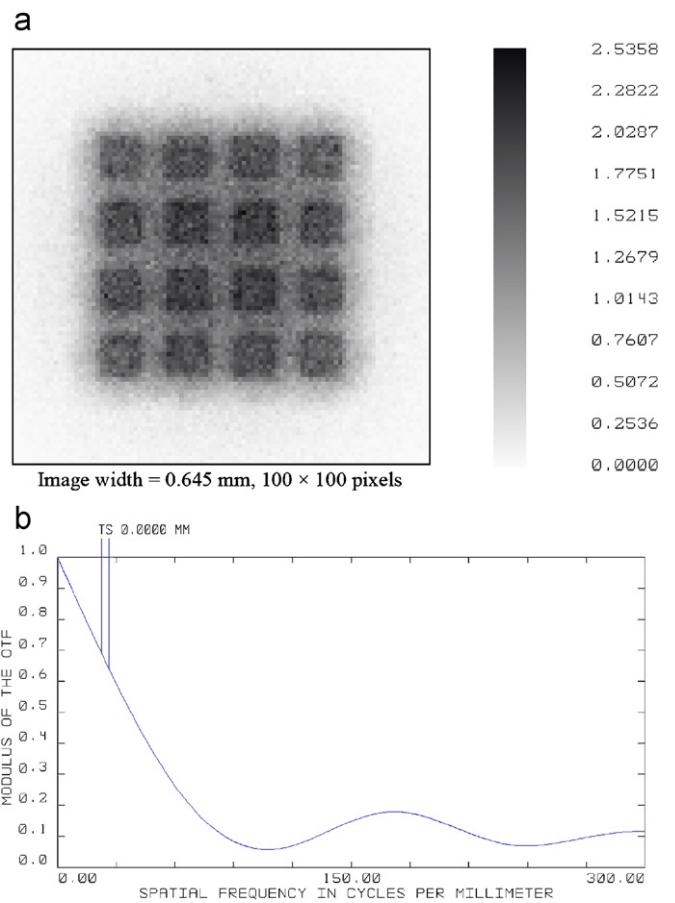


Fig. 2. Results of imaging simulation. (a) Geometric image analysis. A mesh # 1500 (5.5 μm wires separated by 16.5 μm) was set as object. Simulation result was shown in 256 grey scale levels. Each pixel size is $6.45 \times 6.45 \mu\text{m}^2$, just same as the parameters of the detector; (b) MTF's for the simple X-ray imaging apparatus with polychromatic light (7, 8.05 and 8.98 keV X-rays) and a spherical compound refractive lens as optical element. The spatial frequency was 56 cycles/mm with 30% contrast, which means the resolution was about 9 μm.

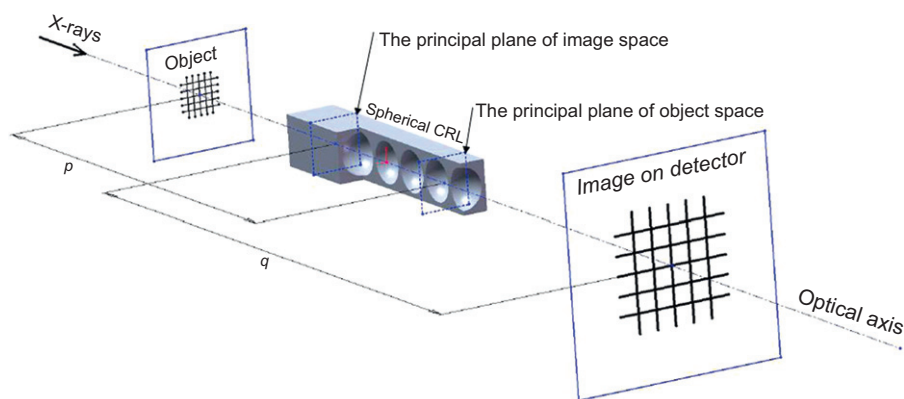


Fig. 3. Schematic diagram of the simple X-ray imaging apparatus.

polychromatic, and spatial frequency was 56 cycles/mm with a contrast of 30%, which means that the resolution is $9\mu\text{m}$ approximately.

4. Experimental results

The experimental setup of the resolution of CRL is composed of three main components: an X-ray tube, a spherical CRL, and an X-ray detector. The schematic diagram of the optical system was shown in Fig. 3. The X-ray tube in the experiment was a homemade X-ray tube with a Cu anode and an apparent source with an area of $0.4 \times 0.4\text{ mm}^2$. The tube voltage was set to 21 kV and the current was 10 mA, which was caused by a standard bremsstrahlung and 8 keV characteristic-line spectra from the tube without filtering. The detector was a Peltier-cooled, 1380×1030 format ($6.45 \times 6.45\mu\text{m}^2$ pixels) charge-coupled device with a fiber-optic-coupled scintillator (Photonic Sciences Ltd., “X-ray Fast Digital Imager”) [20].

Image of mesh was processed to subtract out the background without mesh. The processed image of mesh I was obtained by $I = I - KI_0$, where I_0 is the image of the source without the mesh, I is the image of the mesh, and K is a variable constant, which can be changed so as to meet the best contrast ($K = 0.6$).

Two gold meshes were used as the objects: gold mesh #600 ($7.7\mu\text{m}$ wires separated by $41.4\mu\text{m}$) and gold mesh #1500 ($5.5\mu\text{m}$ wires separated by $16.5\mu\text{m}$). The images were shown in Figs. 4 and 5. Gold mesh #600 was put in the place where there is 152 mm away from the principal plane of object space of the lens, and a $3\times$ image was formed in the place 452 mm behind the principal plane of image space of the lens. The FOV is $808\mu\text{m}$. Gold mesh #1500 and X-ray detector was put exactly the same as the parameters in the simulation ($p = 133\text{ mm}$, $q = 798\text{ mm}$) with a magnification of $M = 6$. The FOV is $707\mu\text{m}$.

As shown in Fig. 4, gold wires with the size of $7.7\mu\text{m}$ were imaged with good contrast. As can be seen in Fig. 5, gold wires with the size of $5.5\mu\text{m}$ can be recognized by the digital camera, which means that the spatial resolution of the simple X-ray imaging apparatus will not worse than $5.5\mu\text{m}$. Because the image-processing techniques are helpful to the contrast of image, the resolution of the apparatus can be better than the simulated resolution of $9\mu\text{m}$. Better resolution will not be achievable for the given experimental conditions unless monochromator and diaphragm are used. As shown in Fig. 6, contrast with the value of 30% can be obtained at higher spatial frequency of 281 cycles/mm, that is, resolution of $1.8\mu\text{m}$, can be achieved using monochro-

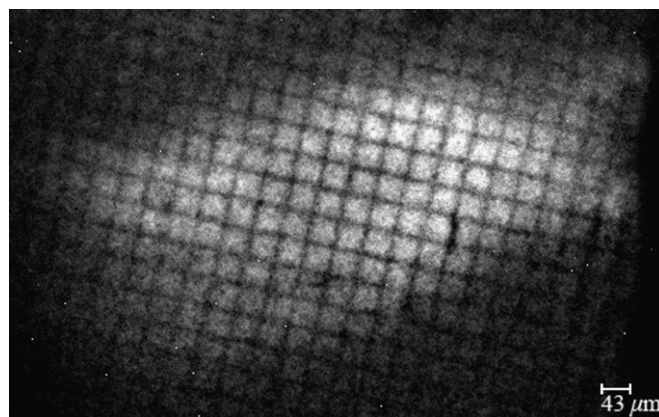


Fig. 4. A $3\times$ image of gold mesh #600 ($7.7\mu\text{m}$ wires separated by $41.4\mu\text{m}$), at 210W for 30 min. The image was cut from the whole image whose FOV was about $800\mu\text{m}$. The non-circular shape of illuminated area was determined by the shape of the source. The blur on the right side of the image was caused by the fault of scintillator in the detector.

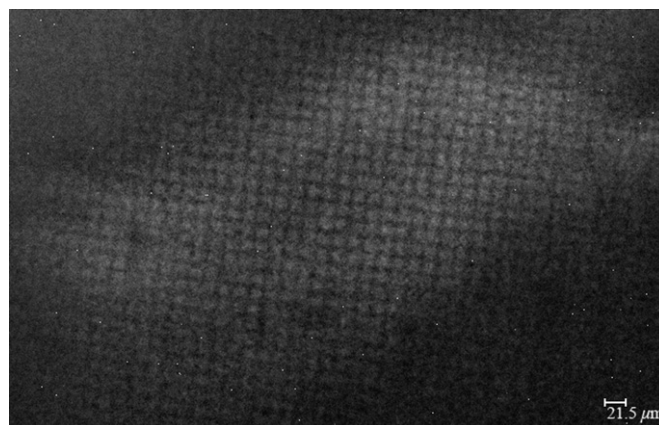


Fig. 5. A $6\times$ image of gold mesh #1500 ($5.5\mu\text{m}$ wires separated by $16.5\mu\text{m}$), at 210W for 45 min. The image was cut from the whole image whose FOV was about $700\mu\text{m}$. The non-circular shape of illuminated area was determined by the shape of the source.

motor for 8.05 keV photon energy. For higher spatial frequency of 1530 cycles/mm with the contrast of 30%, resolution of 327 nm may be obtained by combining monochromator for 8.05 keV and $50\mu\text{m}$ diameter diaphragm at the front of the lens.

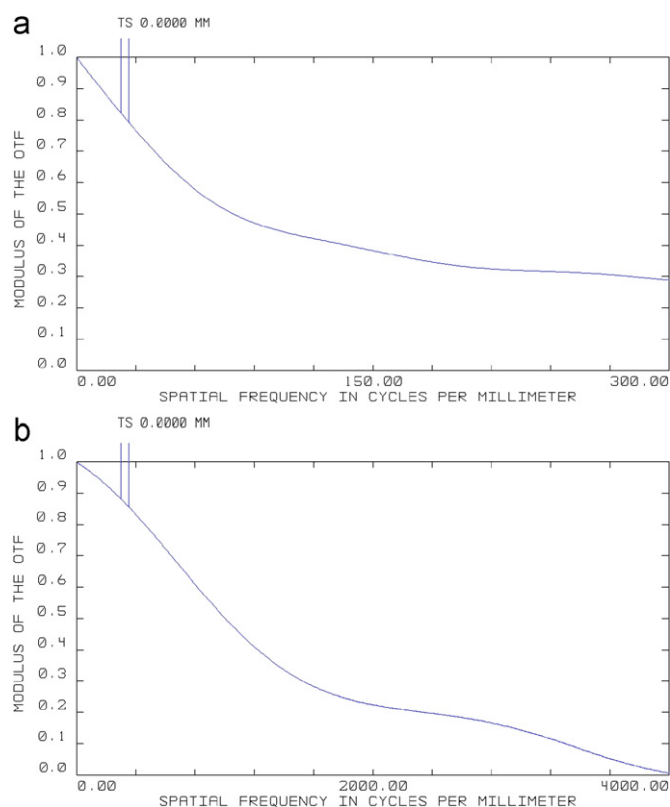


Fig. 6. MTF's for the simple X-ray imaging apparatus with a spherical compound refractive lens and monochromator or both monochromator and diaphragm. (a) Using monochromator for 8.05 keV. The spatial frequency was 281 cycles/mm at 30% contrast, 1.8 μm resolution in another word; (b) Using both monochromator for 8.05 keV and 50 μm diameter diaphragm. The spatial frequency was 1530 cycles/mm at 30% contrast, which means resolution of 327 nm.

5. Conclusion

Imaging experiment shows that the spherical compound refractive lens may be a promising imaging optical element for

hard X-rays with a resolution better than 5 μm . Resolution of CRL can be enhanced by using monochromator and diaphragm.

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