MEASUREMENT OF SPHERICAL COMPOUND REFRACTIVE X-RAY LENS AT ANKA SYNCHROTRON RADIATION SOURCE

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Parameters of compound refractive X-ray lens were measured at ANKA synchrotron radiation source. The lens consists of 224 spherical concave epoxy microlenses formed inside glass capillary. The curvature radius of individual microlens is equal to 100 microns. Measured were: X-ray focal spot, lens focal length and gain in intensity. The energy of X-ray beam was equal to 12 keV and 14 keV. It is shown that when X-ray lens is used, the gain in intensity of the X-ray beam in some cases may exceed value of 100. Tested lens is suitable to focus X-rays into, at least, 2-microns in size spot.

Introduction

Micron-sized X-ray beams are widely used in science and technique. Also there is a great interest in nano-sized X-ray beams, which may be used for producing nanostructures by the method like LIGA. The more useful method for production micro-beams is to focus synchrotron X-rays by any of optics. There are a lot of X-ray devices suitable to do it: Kirkpatrick-Baez X-ray optics, curved multilaer mirrors, single taper or parabolic capillaries, Kumakhov lenses, zone plates and Bragg- Fresnel lenses, compound refractive X-ray lenses.

Compound refractive lenses for X-rays (CRLs) are new elements of optics for the first time proposed and tested by A. Snigirev, V. Kohn, I. Snigireva and B. Lengeler [1]. It consists of a large number N of individual concave cylindrical, spherical or parabolic unit lenses made from low-Z material and placed inline. The focal length of the CRLs is reduced by N times in comparison with the focal length of the individual lens and is equal to 10-100 cm for 8-30 keV X-rays. The lens work as ordinary lens for visual light and lens formula is also valid to describe its operation. The formula is written as:

$$\frac{1}{a}+\frac{1}{b}=\frac{1}{f}\ , \qquad (1)$$

where a is distance from the source to lens, b is distance from the lens to source image, f - lens focal length. The size of the source image S_1, as in the case of visual optics, is related to the source size S by the equation:

$$S_1 = S\frac{f}{a-f}\ . \qquad (2)$$

In the case of synchrotron radiation the distance between the source and the lens is high enough and equals, as a rule, to 10-50 m; the size of the source is also, as a rule, less than 1000 microns. When refractive lens with a focal length equal to approximately 10 cm is used, expected size of source image may be equal to some microns in according to formula 2. This is a way for obtaining micro and nano-sized X-ray beams.

Lens parameters

The focal length f of a compound refractive lens consisting of N individual biconcave spherical lens is determined by the following ratio:

$$f=\frac{R}{2\delta N}\ , \qquad (3)$$

where *R*- curvature radius of an individual lens, (1-δ) is real part of the complex refractive index n for the media, where n= 1–δ–iβ, β is imaginary part of refractive index.

There are same ways to design CRL: it may be produced by pressing or lithographic technique. We proposed to form spherical concave lenses inside glass capillary [2].This idea is based on a fact that a drop of liquid putt into capillary takes a form of biconcave lens. We found that the microlenses inside the capillary were spherical, and the bubble radius of curvature was equal to the capillary radius [3]. Investigations of lens parameters with synchrotron radiation at Stanford Synchrotron Radiation Laboratory and Advanced Photon Source confirm that there is a nice accordance between measured lens focal length and calculated one based on above assumption [4]. Here we present results on focusing experiments with a CRL at ANKA synchrotron.

The lens was designed in Institute of Applied Physics Problems of Belarus State University. The lens consists of 224 spherical epoxy microlenses formed inside glass capillary with curvature radius equal to 100 microns. Fig.1 shows some of microlenses inside glass capillary. Black figures are air bubbles. Lens length is equal to 69 mm.

The individual epoxy lenses inside of the glass capillary are spherical ones with the curvature radius equal to 100 microns. Spherical lenses may be characterized by the following set of parameters: lens focal length f, absorption aperture radius $R_a = (2R/\mu N)^{1/2}$, parabolic aperture radius $R_p = (2R^3\lambda/\delta N)^{1/4}$, and the diffraction radius $R_{diff.} = 0.61\ \lambda f/R_a$, that characterises diffraction blurring of the focused beam. The parameters in these equations are the capillary radius R, number of lenses N, the linear absorption coefficient μ for the lens material, and the wavelength λ. The parabolic aperture radius R_p is the central portion of the spherical lens that focuses X-rays to the same point.

The lens was used to focus X-rays with energy 12 keV and 14 keV. Calculations show that for 12 keV X-rays parabolic aperture radius of the lens is R_p=27 microns for the case of the discussed lens (R= 100 microns, N= 224). The absorption lens aperture radius Ra for the lens is equal to 69 microns. The same values for 14 keV X-rays are: R_p=28 microns, R_a=94 microns Lens focal length f calculated by formula 1 for 12 keV and 14 keV is equal to 133 mm and 180 mm respectively. The lens length is equal to 69 mm and it is "thick enough" comparing to lens focal length. The focal length f_t of a thick lens may be calculated by the next formula [5]:

$$\frac{f_t}{f} = \frac{\left(\frac{t}{f}\right)^{1/2}}{\sin\left(\frac{t}{f}\right)^{1/2}}, \qquad (4)$$

where t is lens length. Result of calculation of f_t : f_t = 145 mm for 12 keV X-rays and f_t = 192 mm for 14 keV X-rays.

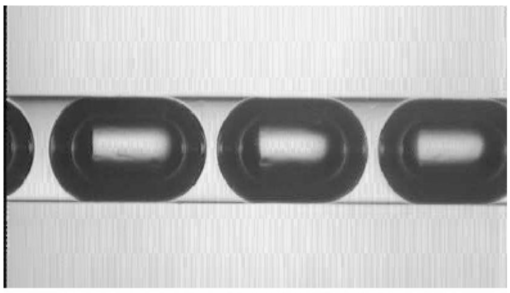

Fig. 1. Concave epoxy microlenses inside glass capillary. Black figures are air bubbles.

Lens measurement

The CRL consisting of 224 spherical concave microlenses set has been characterized for 12 keV and 14 keV X-rays at the ANKA-FLUO experimental station situated at a bending magnet of the ANKA synchrotron light source. The energy was monochromatized by a W/BC4 double multilayer monochromator with 2% bandwidth. For the measurement of the beamsize the lens was placed on a five axis positioning device and exactly oriented in the direction of the x-ray beam. The distance *a* between source and lens was equal to 12.7 m. The size of the source *s*: 800x250μm FWHM. The source size can be reduced by a 0.1mm x 0.1 mm^2 slit #1 placed at a distance 4.7 m to the source. There was one more slit #2 placed at 1m distance from lens. The slit size was 0.1mm x 0.08 mm^2. It was also possible to hold slits in opening mode.

Measured were beam size at different distance to the lens and lens transmission. The distance where minimum value of beam size observed was considered as lens image distance. The beam size was derivated from knife edge scans conducted around the focus position derived with the x-ray camera. A 0.5μm thin Permalloy structure was chosen and the edges have been scanned with 0.5μm or 1 μm resolution. Characteristic Fe atom X-rays emitted by Permalloy structure were registered by X-ray camera. The measured profile of the edge is the convolution of the Fe concentration function (approximated by a step function) and the profile of the x-ray beam. As the step function converts the convolution in to a simple integration, the measured function is the error function if the beam profile is a Gaussian. Thus an error function has been fitted to the knife edge data. Fitting a gauss function to the derivative is equivalent; nevertheless numerical derivating adds a considerable amount of noise to the data.

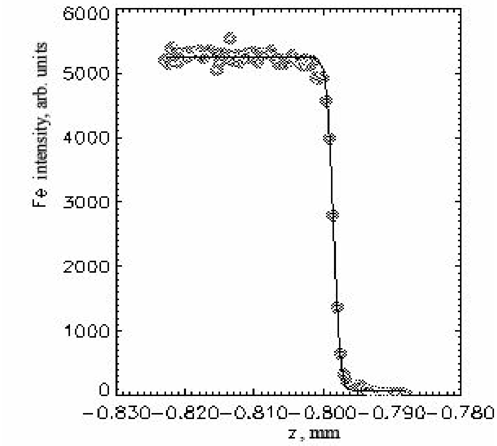

Fig.2 Fit of error function to vertical scan over lithographic structure.

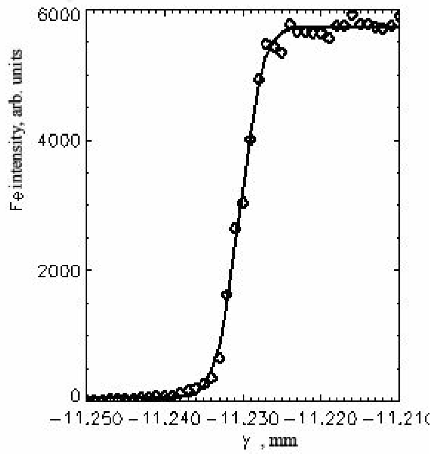

Fig. 3. Fit of error function to horizontal scan over lithographic structure.

Fig.2 and Fig.3 shows fit of error function to vertical and horizontal scan over lithographic structure correspondingly.

To determine gain in intensity of the beam due to focusing by the lens next procedure was applied. The lens was removed and the fluorescence intensity resulting from a Permalloy square of 50μm size was measured. This intensity was compared to the intensity of the focussed beam and the area of the focussed beam was calculated with $A=2\pi\sigma_x\sigma_y$ with being the gaussian beamsize (FWHM value/2.35). With closed front end slits the gain factor for a smaller source can be obtained. Therefore two values for the gain are given in Table 1.and Table 2. For the ANKA source however closing slits cannot improve the gain.

Table 1. Parameters of spherical compound X-ray lens for 12 keV X-rays

Energy, keV	**12**	**12**
Size of slit #1, mm^2	1 x 1	0.1 x 0.1
Measured image distance, mm	146	147
Calculated image distance, mm	147	147
Calculated lens focal length f_t , mm	145	145
Measured horizontal focal size, µm	10.4	4.1
Measured vertical focal size, µm	2.2	1.7
Gain	34/31	113/18
Transmission	9.5%	9.5%

Table 2. Parameters of spherical compound X-ray lens for 14 keV X-rays

Energy, keV	**14**	**14**
Size of slit # 1, mm^2	1 x 1	0.1 x 0.1
Measured Image distance, mm	195	196
Calculated image distance, mm	195	195
Calculated lens focal length f_t , mm	192	192
Measured horizontal focal size, µm	12.2	6.3
Measured vertical focal size, µm	3.0	2.1
Gain	43/40	162 /22
Transmission	21.5%	21.5%

Conclusions

Investigations shown that tested lens is suitable to focus 12 keV-14 keV X-rays into some microns in size spots. Calculated lens focal length is in a good agreement with measured one. The lens parameters may be improved my increasing lens transparency. Also lenses with shorter lens focal length may be forming inside capillary with inner diameter equals to 100 microns. In this case the lenses may be used for nano-focusing.

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