REFRACTIVE LENS FOR HARD X-RAYS

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The refractive lens for hard X-rays on the base of glass capillary is presented. The fabrication techniques for lens production are described. The model of refractive lens for hard X-ray is proposed. The model assume that the compound lens work similar one thin lens the complex refraction index of which is following: n=1-δ N + i β N. On the base of this model the parameters of focussed beam are calculated and the images of object are constructed.

Introduction

The application opportunity of refracting optics methods in a x-ray range attracted the researchers rather for a long time. Accounts showed that for x-ray radiation due to large absorption in a soft range of a spectrum (usually energy of photons < 5 keV) and weak refraction in hard range refracting lenses are inefficient. Nevertheless as showed estimations such lenses were possible but required significant efforts on their manufacturing and could be used only with powerful x-ray sources [1].

With development of synchrotron sources of the third generation it was suggested to use refracting lenses as a collimator for a hard x-rays. Was noted, that the realisable optical devices on the basis of refracting lenses will have a number of advantages in comparison with for example mirrors [2]. However the lack of experimental data about X-ray parameters of substances in a hard x-rays and large focal distance of lenses were the basic arguments against using of refracting lenses [3].

In 1996 Snigirev has made the first refracting lens for 15 keV X-rays [4]. The idea of proposed lens consists in using of a set of lenses made from low-Z material. The compound lens was made as a 30 cylindrical holes drilled in Al plate, had focal distance about 2 m and formed focal spot of 8 micron in size. However such lens could not be applied as a image-forming lens.

To the present moment of time there is the whole number of refracting x-ray lens designs. However as image-forming lens can be considered following: a parabolic lens [5], prepared by a pressing method of individual lenses; and microcapillary lens [6], developed in author's collective. The experimental researches have shown a basic opportunity to focus hard x-rays not only from synchrotron of sources but from powerful x-ray tube [4,5,7,8]. Nevertheless the whole line of questions connected to lens optimization remain open and mentions both technology of manufacturing of lenses and theory of distribution of x-ray in system of refracting lenses.

Fabrication technique

The idea of microcapillary lens is based on the well-known effect that a drop of water in glass capillary under action of natural surface tension forces takes the bi-concave form. The schematic view of developed microcapillary lens is shown on fig. 1. Glass capillary filled with a set of bi-concave drops-lenses allows to reduce focal distance of compound lens in comparison with one lens in N of time, where N number of drops - lenses.

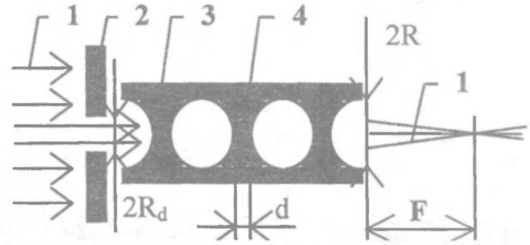

Fig. 1. Schematic view of the microcapillary lens. 1-X-ray beam; 2-diaphragm; 3- glass capillary; 4- liquid.

The essential features of the lens material are: weak absorption of x-rays; radiating stability; homogeneous substance and its technological suitability for manufacturing of solidified lenses. As a material polymers were chosen, basic elements of which are carbon and hydrogen. Commercially available optical epoxy glues was applied, which hold the shape under hardening.

Two techniques for microcapillary lenses preparation were developed. First is based on spontaneous collapsing of a liquid film inside of glass capillary resulting to formation of periodically located drops-lenses. The schematic view of lens formation process is shown on fig. 2.

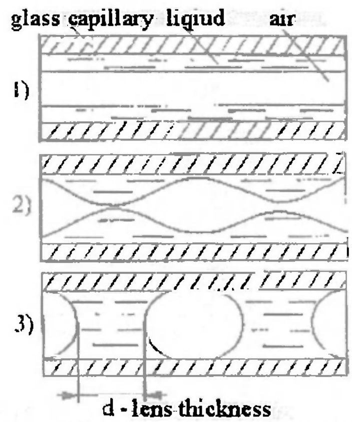

Fig.2. Stages of formation process of the microcapillary lens: 1) thin film of liquid inside of capillary; 2) capillary waves on the liquid film; 3) collapsed film as a set of lenses.

The individual lenses were characterized by thickness in a narrow part of a lens, which linearly depends on radius of glass capillary [6]:

$$d=3R-60 \text{ microns}, \quad (1)$$

where d – is the thickness of a lens, R- is the capillary radius. The given correlation is true for lenses formed in 50-500 microns in radius capillary.

The second technique consists in consecutive formation of bi-concave lenses in glass capillary with help of additional thin capillary-needle. The schematic view of installation for lens fabrication is shown on fig. 3.

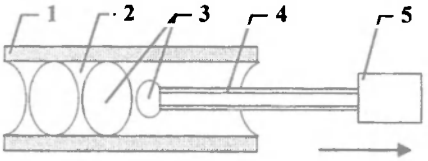

Fig. 3. Schematic view of the setup for the microcapillary lens fabrication. 1- glass capillary tube; 2-liquid; 3-air bubbles; 4- injector capillary-needle; 5- cylinder with a compressed air.

In use such technique the lenses with thickness *of 10-50 micron in glass capillary 100-500 micron in* radius were produced. The photo of a refractive lens is shown on fig. 4.

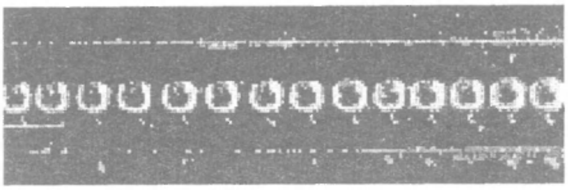

Fig. 4. Visible light microscope image of the refractive lens. The diameter of the capillary is equal to 0.8mm.

With the help of digital optical microscope the lens form was investigated. Was accepted that a line on a photo (fig.5.) dividing dark and light parts characterizes the form of a lens.

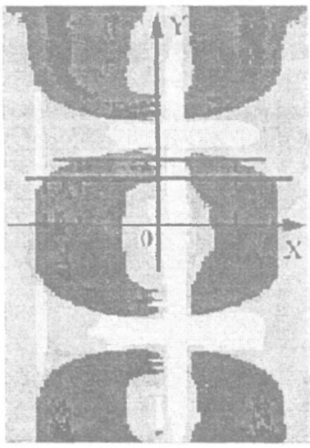

Fig.5. Visible light microscope image of the microcapillary lens and the scheme of lens profile measurements. The radius of capillary is equal to 390 microns.

Was taken into account that the given line is deformed in result of beam refractions on lens-capillary and capillary-air boundaries. As shown in fig. 6. microcapillary lens is spherical with radius of curvature equal to radius of the capillary channel.

Investigations of radiating stability of a lens material have shown that the chemical characteristics of epoxy resin much vary at radiating doze appropriate to 10° Gr. However as have shown experiments the damage of lenses did not occur and its form remains constant [8]. That gives a basis for the statement about radiating stability of a lens at dozes about 10^8 Gr.

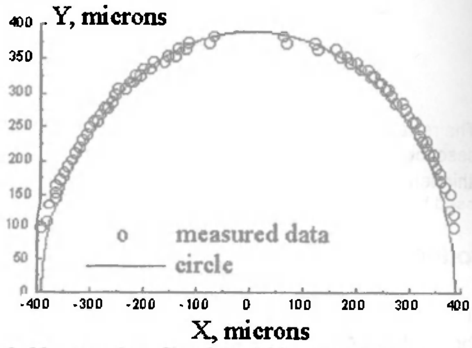

Fig.6. Measured profile of the 390 microns in radius lens.

Model of the refractive lens

So wave length of hard x-ray is much less than general sizes of lenses, the principles of geometrical optics for the description of distribution of x-ray radiation in system of lenses are appropriated.

We shall consider distribution of a x-ray beam through a set of spherical lenses. In view of weak refracting ability of substances in a x-ray range of a spectrum, the using of a set of lenses allows to reduce focal distance of system up to value 1-2 m. As the sizes of a lens about 100-500 micron and the source places at distance exceeding focal distance, it is possible to accept (see fig.7.), that the x-ray beams are parallel of an optical axis of system, and the absolute angle of a beam to an optical axis is extremely small (about 10^{-3}-10^{-4}). According to this the Snell's law for an incident beam are following:

$$n \,\mathrm{Sin}\,(\phi-\alpha_1) = \mathrm{Sin}\,(\phi-\alpha_2)\,,$$
$$\mathrm{Sin}\,(\phi+\alpha_1) = n\,\mathrm{Sin}\,(\phi+\alpha_2)\,. \qquad (2)$$

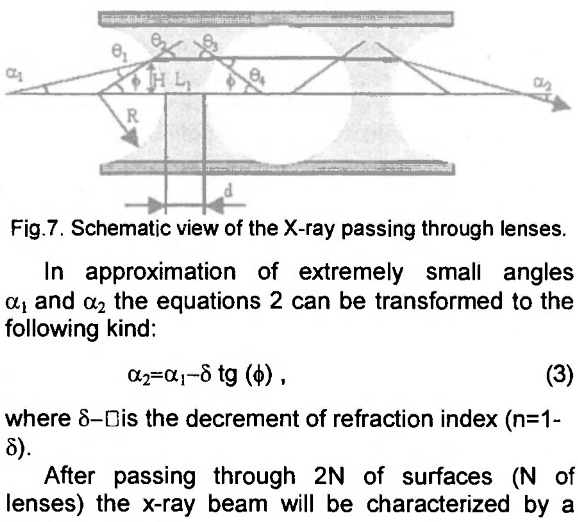

Fig.7. Schematic view of the X-ray passing through lenses.

In approximation of extremely small angles α_1 and α_2 the equations 2 can be transformed to the following kind:

$$\alpha_2=\alpha_1-\delta\ \mathrm{tg}\,(\phi)\,, \qquad (3)$$

where δ–□is the decrement of refraction index ($n=1-\delta$).

After passing through 2N of surfaces (N of lenses) the x-ray beam will be characterized by a angle α_2 equals:

$$\alpha_2=\alpha_1-2□N\,\delta\ \mathrm{tg}\,(\phi)\,, \qquad (4)$$

where $\mathrm{tg}\,(\phi)=H/\,(R^2-H^2)^{1/2}$.

Focal distance of compound lens as follows form eq.4. under $H\to0$ is equal:

$$F=R\,/\,(2\,\delta\,N)\,. \qquad (5)$$

This is supported by experimental results [4,5,8].

As optical way of x-ray beams through the system of N lenses is increased in N times to comparison with way in one lens, it is possible to propose the lens model which assume that system of lenses acts as one thin lens a complex refraction index of lens substance is expressed as:

$$n=1-\delta N + i\beta N, \qquad (6)$$

where β - is the index related to the absorption of X-rays.

Results and discussions

On the base of lens model the size of focussed beam can be calculated. From eq. 4 the dependence of spot size in focal plane R_f on the diaphragm radius R_d can be approximated by:

$$R_f=1/2\,R_d^3/R^2 + 3/8\,R_d^5/R^4 + 15/48\,R_d^7/R^6 + \ldots \qquad (7)$$

This analytical result was compared with the results of ray tracing simulations made for compound lens and for models of lens. As have shown from fig.8. the model is good for estimates of focused X-ray beam, when the lens is small in size.

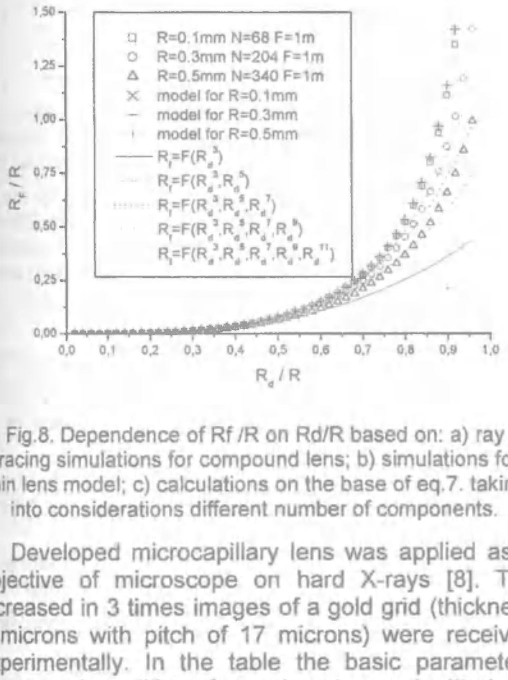

Fig.8. Dependence of Rf /R on Rd/R based on: a) ray tracing simulations for compound lens; b) simulations for thin lens model; c) calculations on the base of eq.7. taking into considerations different number of components.

Developed microcapillary lens was applied as a objective of microscope on hard X-rays [8]. The increased in 3 times images of a gold grid (thickness 5 microns with pitch of 17 microns) were received experimentally. In the table the basic parameters lenses and condition of experiment are submitted.

Table.

Parameters of lenses and condition of experiments.

	Lens 1	Lens 2
Lens material	epoxy glue	Glycerol
Radius of lens, microns	104	400
Number of lenses	71	185
Energy of X-rays, KeV	18.3	17.1
Focal distance, m	0.9	1.2
Magnification	3	3.2
Distance to the image, m	1.2	2
Distance to the object, m	3.6	5

The developed lens model was used for construction of the increased image of the object formed by a refractive microcapillary lens. Was assumed that the image is formed in parallel X-rays since the distance from lens to X-ray source is 45 m. On fig. 9(a,b) the superposition of grid images received experimentally and constructed are shown. It is visible, that the accounts on the base of thin lens model precisely describe the experimental data.

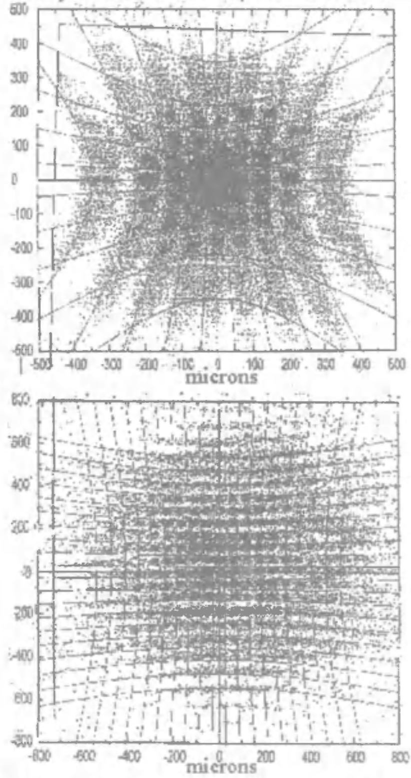

Fig.9. The superposiioned grid images received experimentally and constructed on the base lens model for the a) lens 1; b) lens 2

Conclusions

The fabrication techniques for microcapillary lens production are described. The model of refractive lens for hard X-ray is proposed. On the base of this model the parameters of focussed beam are calculated and the grid images are constructed. It is necessary to note, that the given model can be used for any form of a individual lens. The application condition of model is the small linear sizes of a lens in comparison with focal distance.

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