Using of a Microcapillary Refractive X-ray Lens for Focusing and Imaging

Yury I. Dudchik, Fadei F. Komarov

Institute of Applied Physics Problems
Belarus State University
Minsk
Belarus

Melvin A. Piestrup,
Charles K. Gary, J. Theodore Cremer,
Heungsup Park

Adelphi Technology, Inc.
San Carlos
California
We have fabricated, tested and used for X-ray imaging microcapillary (bubble) compound refractive lenses for 7-20 keV X-rays.

The lenses are composed of micro-bubbles embedded in epoxy. The bubbles were formed in epoxy inside glass capillaries with diameter in the range between 100 microns and 500 microns.

The interface between the bubbles formed 90 to 350 bi-concave microlenses, which are suitable for focusing X-rays.

The individual microlenses are spherical ones. The radius of the lenses is equal to capillary one.

The lens’s parameters were measured at beamline 2-3 at the Stanford Synchrotron Radiation Laboratory (SSRL) and at beamline 5BM-D-DND at the Advanced Photon Source.

A simple X-ray microscope consisting of X-ray tube, microcapillary refractive X-ray lens and CCD-camera is proposed.
X-RAY LENS

Refractive index

\[ n = 1 - \delta - i\beta \quad (1) \]

\[ \delta = 0.5 \left( \frac{E_p}{E} \right)^2 \sim 10^{-4} - 10^{-7}, \quad \beta = \frac{1}{4\pi} \mu \lambda \sim 10^{-3} - 10^{-5} \]

Ep – plasmon energy,
E – photon energy,
\( \lambda \) – wavelength,
\( \mu \) – absorption coefficient.

Lens focal length

\[ F = \frac{R}{2\delta} \quad (2) \]

For SiO2: \( \delta = 2 \times 10^{-5} \), \( \beta = 6 \times 10^{-5} \) for 5 keV photons

For \( R = 0.1 \text{ mm} \) \( \Rightarrow F = 2.5 \text{ m} \)
Compound lens focal length: \( F = \frac{R}{2\delta N} \) \( (1) \),

\( N \) – number of individual lenses


**15 keV X-rays**

R=0.3 mm, N=30, intensity gain G=3

![Diagram showing 15 keV X-rays](image-url)
Microcapillary X-ray lens

Photographs of bubble compound refractive lens
EPOXY FORMULA $C_{100}H_{200}O_{20}N$
Capillary diameter = 0.8 mm

Capillary diameter = 0.2 mm
Lens fabrication

Fig. 1. Schematic view of the setup for the lens fabrication.

1-glass capillary tube; 2-glue; 3-air bubbles; 4-injector needle; 5- cylinder with a compressed air.

Results:
1. Lenses are spherical.

2. The thickness of the lens (space between bubbles) may be done up to 10 microns
SPHERICAL ABERRATIONS AND SPOT SIZE OF THE BUBBLE LENS

Fig. 1 Paths of X-rays forming a focal spot of the X-ray lens.

The photon energy is 8 keV; the radius of the lens is 100 microns, the number of microlenses is equal to 103.
We have produced a set of lenses in the form of glass capillary with diameters equal to 200 microns and to 100 microns and filled by 100-150 microlenses. The parameters of this lenses are described below.

**LENS PARAMETERS**

1. The lens curvature radius = radius of capillary.

2. Absorption limits the aperture of the lens to $2R_a$

$$R_a = (2R/\mu N)^{1/2} \quad (1)$$

$\mu$- linear absorption coefficient for lens material.

3. Only central part of the lens with radius $R_p$ focuses the X-ray beam into the same point.

$$R_p = (2R^3\lambda/\delta N)^{1/4} \quad (2)$$

4. Diffraction blurring of the focused X-ray beam:

$$R_{\text{diff.}} = 0.61 \lambda f/R_a \quad (3)$$

Table 1. Calculated lens parameters for 8 keV X-rays

<table>
<thead>
<tr>
<th></th>
<th>2R, $\mu m$</th>
<th>N</th>
<th>F, cm</th>
<th>2R&lt;sub&gt;a&lt;/sub&gt;, $\mu m$</th>
<th>2R&lt;sub&gt;p&lt;/sub&gt;, $\mu m$</th>
<th>2R&lt;sub&gt;diff.&lt;/sub&gt;, $\mu m$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>200</td>
<td>200</td>
<td>82</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>150</td>
<td>150</td>
<td>100</td>
<td>100</td>
<td>116</td>
</tr>
<tr>
<td></td>
<td>6.6</td>
<td>4.4</td>
<td>13.2</td>
<td>34</td>
<td>32</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td>82</td>
<td>66</td>
<td>116</td>
<td>94</td>
<td>94</td>
<td>0.22</td>
</tr>
<tr>
<td></td>
<td>34</td>
<td>32</td>
<td>60</td>
<td>54</td>
<td>54</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td>0.3</td>
<td>0.22</td>
<td>0.4</td>
<td>0.34</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The experiments were performed at beamline 2-3 on Stanford Synchrotron Radiation Laboratory.

The approximate source size was **0.44 x 1.7 mm**².

The distance from the source to lens was **L=16.81 meters**.

Lens formula: \( \frac{1}{a} + \frac{1}{b} = \frac{1}{f} \)

Focal spot size = source size \( \frac{(L-f)}{f} \)

Demagnification: \( \frac{1681}{13} = 130 \)

for \( f=13 \text{ cm} \)

Experimental apparatus for measuring the profile of a focused X-ray beam and establish the image distance is shown below:
The focused beam profiles results from the lens #4-1 in the form of glass capillary filled by 102 bubbles. Capillary diameter = 200 microns.

The source size of **0.44 mm** is focused to the minimum spot FWHM of **5 μm**, at distances of **13 cm** from the lens.
Profile of the focal spot size as a function of distance from the lens

The figure shows that the waist of the X-ray beam is converging to minimum at approximately 13 cm to the lens.

Measured transmission profiles of the lens at 8 keV
<table>
<thead>
<tr>
<th>Bubble Lens designation</th>
<th>1-1</th>
<th>3-4</th>
<th>3-3</th>
<th>4-1</th>
<th>4-1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photon Energy (keV)</td>
<td>12</td>
<td>9</td>
<td>8</td>
<td>8</td>
<td>7</td>
</tr>
<tr>
<td>Number of lenses</td>
<td>90</td>
<td>103</td>
<td>93</td>
<td>102</td>
<td>102</td>
</tr>
<tr>
<td>R, Radius of Curvature (μm)</td>
<td>165</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Calculated Focal Length (cm)</td>
<td>52.8</td>
<td>15.7</td>
<td>13.8</td>
<td>12.55</td>
<td>9.6</td>
</tr>
<tr>
<td>Calculated Image Distance (cm)</td>
<td>54.5</td>
<td>15.8</td>
<td>13.9</td>
<td>12.6</td>
<td>9.7</td>
</tr>
<tr>
<td>Measured Image Distance (cm)</td>
<td>32</td>
<td>17.5</td>
<td>13</td>
<td>14</td>
<td>10</td>
</tr>
<tr>
<td>Calculated Vertical Minimum Waist Diameter (μm)</td>
<td>15.1</td>
<td>4.4</td>
<td>3.9</td>
<td>3.2</td>
<td>2.7</td>
</tr>
<tr>
<td>Measured Vertical Minimum Waist Diameter (μm)</td>
<td>12.8</td>
<td>3.9</td>
<td>4.8</td>
<td>2.7</td>
<td>4</td>
</tr>
<tr>
<td>Measured Peak Transmission</td>
<td>36</td>
<td>24%</td>
<td>16%</td>
<td>27%</td>
<td>5%</td>
</tr>
<tr>
<td>Calculated 2D-Gain</td>
<td>16.6</td>
<td>25.6</td>
<td>16.9</td>
<td>28.9</td>
<td>6.0</td>
</tr>
<tr>
<td>Measured 2D-Gain</td>
<td>8.9</td>
<td>13.4</td>
<td>**</td>
<td>25.5</td>
<td>**</td>
</tr>
</tbody>
</table>
The bubble lens has five attributes that make it attractive for use for imaging and focusing:

1. Because of the nature of the physics forming the bubble, the lens surface quality is extremely good, probably much better than any other method for forming the lens.

2. The capillary “enclosure” insures that the series of unit lenses or bubbles are extremely well aligned coaxially.

3. The minimum thickness of the lens, \( d \), can be made extremely thin.

4. The radius of curvature can be made to be much smaller than other methods of fabrication.

5. The method and materials of fabrication result in an extremely robust and inexpensive CRL.

Publications:


**IMAGING WITH X-RAYS**

*Projection X-ray microscopy*

![Diagram of X-ray source, object, and CCD-camera setup.]

- **X-ray source (tube)**
- **Object**
- **CCD-camera**

**Resolution** ~ **X-ray source size**

**X-ray tube focal spot** ~ **5 microns**

**Disadvantage of the method:**

1. It needs high voltage (100 kVp) to focus electrons into micron-sized spot
2. The position of a focal spot of electron beam at anode plane isn’t stable in time.
X- RAY IMAGING WITH LENS

Lens formula: \( \frac{1}{a} + \frac{1}{b} = \frac{1}{f} \),

\( f \)- focal length

Advantage: ordinary X-ray tube is used

Resolution of the method is limited by diffraction:

\[ R_{\text{diff.}} = 0.61 \frac{\lambda}{f/R} \]

\( \lambda \)-wavelength, \( f \)-focal length

\[ R_{\text{diff.}} \approx 0.1-0.3 \text{ microns} \]
FIELD OF VIEW OF THE IMAGING SYSTEM

Fig.1. Focusing of X-rays from a point source.

Fig.2. Calculations of transmission angle.

Fig.3 With lens imaging of X-ray source.
X-ray imaging experiments in Institute of Applied physics Problems (BELARUS)

LENS PARAMETERS

Lens curvature radius: $R = 100$ microns
Number of individual lenses: $N = 137$
Lens focal length for 8 keV X-rays
  \[ F = 100 \text{ mm} \]
Lens absorption aperture:
  \[ 2R_a = 100 \text{ microns} \]
Lens parabolic aperture:
  \[ 2R_p = 56 \text{ microns} \]
Transmission for 8-keV X-rays = 0.2
Expected resolution = 0.4 microns

X-ray tube parameters

Russian Tube BSV-19 with Cu anode
  Focal spot size: $0.4 \text{ mm} \times 8 \text{ mm}$
  Voltage: $32 \text{ kVp}$
  Current: $14 \text{ mA}$
Imaging device:
  Marshal B/W CMOS camera;
  $510 \times 492$ (10µm X 13.5 µm) pixels
RESULTS of EXPERIMENTS

1. Image of the X-ray tube focal spot.
   a=14 cm  b=51 cm  magnification=4

2. Mesh # 400 image.
   a=13 cm  b=51 cm  magnification =4
RESULTS of EXPERIMENTS

3. Mesh #1000
Magnification=4
a=13 cm b=51 cm

Mesh #1000 is gold one consisting of 5-microns gold wires

#1000 means that grid period is 1000/ inch
Adelphi Technology, Inc., San Carlos, California

Experiment details:
X-ray lens: focal length = 13.5 cm for 8 keV X-rays; absorption aperture = 150 microns; transmission = 0.27.
X-ray tube: An Oxford Instruments X-ray tube, model XTF5010A, copper anode, source size = 0.5 mm X 1.5 mm, Voltage = 18 kV, current = 0.75 mA.

A comparison of the field of views: (a) A 5.4 X image of 2000 grid mesh (grid period is 2000/inch) using synchrotron source. (b) A 4.5 X image of a 400 grid mesh (400/inch) using an x-ray tube. Since (a) is so much smaller than (b) we have increased (a)’s size for visual clarity.
With lens X-ray image of the spinal column of Paracheirodon Innesi (neon tetra aquarium fish) obtained using a bubble CRL and an unfiltered X-ray tube.

**Conclusions**

1. Microcapillary lens is suitable for imaging applications with X-ray tube as a source.
2. Expected spatial resolution is 0.2-0.5 microns.
3. Achieved resolution is 3 microns.
List of organizations where Microcapillary (bubble) Lens was tested or (and) used:

1. **SPring-8 (Japan).** The Lens was tested and used as objective for X-ray microscope. Results are published.
2. **Adelphi Tecnhnology (USA).** The Lens was tested at Stanford Synchrotron Radiation Laboratory and at APS and is used as objective for table-top X-ray microscope. Results are published.
3. **Institute of Crystallography (Russia).** The Lens is used as objective for table-top microscope. Results are published.
4. **Laboratory of Plasma Studies, Cornell University (USA).** The lens was used to measure X pinch size. Results are published.
5. **Kumakhov’s Institute of Roentgen Optics (Russia).** The lens was tested.
6. **MRC Laboratory of Molecular Biology (England).** The lens was tested by Dr. Uli Arndt for forming parallel X-ray beam from a microfocus X-ray tube.
7. **Synchrotron light source ANKA (Germany).** The lens was tested and compared with the lens designed by V.Nazmov.
Thank your very much for your interest to the problem!