Laboratory X-ray microscopy with reflective – refractive lens system

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1. Abstract
Compound refractive lens (CRL), consisting of a number of in-line placed concave microlenses made of low-Z material, is a unique imaging X-ray device. An experiment combining the CRL manufactured by the method described in [1] and working as an objective with the reflective micromirror as a condenser and X-ray microfocus source is presented. The system was used as an X-ray microscope working at 8 keV X-rays and also for demonstration of demagnified imaging.

2. Introduction
High resolution x-ray microscopy based on the laboratory x-ray sources has already reached the level of commercial products [2, 3]. Achievable resolution currently breaks the 50 nm level. Such systems, typically, use a table top x-ray source, collecting optics and objective optics. While there are several options for the collecting optics (capillary, zone plate, grazing incidence mirrors, etc.), zone plate is used as the objective optics in the majority of high resolution systems. The objective optics creates a geometrically enlarged image of the sample on the imaging detector.

Still, there are especially industrial and engineering applications, where the resolution of the order of ~ 1 µm is sufficient. These include small electronic parts imaging, imaging XRF, etc. The other large application area, which was actually the original reason for our work, are the university teaching activities. All these experiments would largely benefit from much lower price of the components. While the zone plate costs 5 kEUR typically, the price of the micromirror or the CRL especially is much lower.

Compound refractive lens (CRL) is generally a refracting X-ray optics. It consists of a number of individual lenses aligned one behind each other with typically ~ 100 µm radius. Originally, CRLs were developed by Snigirev [4], were it focused only in one direction using a set of holes. The CRL developed by Dudchik [1], which is called a Microcapillary lens, is based on the same principle, but consists of a number of precisely aligned gas (air) bubbles inside the plastic filled capillary. The theoretical resolution is ≥ 0.2 µm and demonstrated measurement at synchrotrons shown ≥ 0.3 µm[5].

Micromirrors are grazing incidence X-ray mirrors developed by Reflex s.r.o. and were used originally as a condenser for Bede Microsource. Ellipsoidal or parabolic gold layered mirrors with
diameter $\sim 1$ mm, length $\sim 50$ mm, source-detector distances $\sim 250 - 600$ mm. The mirrors are generally manufactured using the replication technology [6]. Different mirror materials were also tested, including Molybdenum instead of Gold and recently also the tests with multilayers inside [7] were undertaken.

3. Experimental setup

X-rays were emitted from the X-ray tube (40 keV, 2 mA, CuK$\alpha$ line, $\sim 50 - 80$ $\mu$m spot size). They were further collected by the Micromirror ME 600 (ellipsoidal mirror, gold coated, source–mirror dist. $x_1 \sim 15$ mm, and source–detector dist. $x_d \sim 600$ mm). This mirror is optimized for 8 keV, however is not optimized for the lens itself. The CRL used in the experiment was a 38 mm long capillary filled with 121 bubbles with $R = 100$ $\mu$m radius. Focal length, calculated and measured at synchrotrons as well, is $\sim 109$ mm if measured from the lens center. Two X-ray detectors were used within the experiment. Reflex RX1 Fast X-ray Camera was used for rough measurements and adjustments. It has 620 $\times$ 460 pixels, $23.5 \times 23.5$ $\mu$m$^2$ each. Prototype of Reflex high resolution $\mu$CRON camera was used for actual measurements. It has 1376 $\times$ 1038 pixels with effective pixel size $\sim 0.645 \times 0.645$ $\mu$m$^2$.

Two gold meshes were used as a sample. One of them had 25 $\mu$m period and 5 $\mu$m thick wires, while the second gold mesh had 85 $\mu$m period.

4. Results

First experiments were done in order to verify the quality of the lens itself. Sample — the mesh with 1000 periods per inch — was placed close to the source. The image created by the lens was then captured by the $\mu$CRON camera with magnification $M = 1/5$. The result after subtracting the source image and further image processing is shown in Figure 1.

The mesh inside the rectangular structure is clearly visible. Mesh period after the demagnification is $\sim 5$ $\mu$m, each of the periods can be perfectly distinguished. Thus, it has been verified that the resolution of the lens and the $\mu$CRON camera is $\sim 1$ $\mu$m.

Tilted rectangular structure containing the image of the mesh is just an artefact. It is due to the combination of the source profile, pinholes and screens used to guide the radiation and image processing.

A combination of the lens and micromirror was the next experiment. It demonstrated the properties of the combination and was used as a testbed for gaining experience for future modifications (not presented here). The mirror was used as the condenser while the lens was used as the objective.

Ideally, the parameters of the mirror and the lens have to be mutually optimised to match each other, however the one used for the tests was not optimised as this is planned in the future. In order to shorten the source–detector distance, and thus increase the signal, the lens was placed into the mirror focus, while the sample was in the focus of the lens ($\sim 200$ mm in front of the lens). Thus only a circle of the sample was illuminated. This relatively unusual arrangement is sometimes used in visible light illumination experiments in order to make the illumination homogeneous.

The beamstop was not used in our experiments. This gave the possibility to study the lens from two different point of views as the resulting image was a composition of source image created by the lens working as a pinhole and image of the mesh created by the lens as an objective. The beamstop was applied later on virtually using the image processing methods.

One of the results after applying the virtual beamstop (removing the pinhole effect) is shown in Figure 2. Only a circle is seen, exactly as expected, with mesh bars visible as shadows. The lens setup was chosen to be have a 1:1 magnification. The image was obtained after 5 minute exposure time.
In fact, the image created by the pinhole was much brighter if compared to the one shown in figure. This is due to absorption inside the lens. The rays creating a pinhole image are going through the center of the lens, where the absorption is the smallest. On the other hand, the objective image is created by rays passing through the lens at the angle and therefore at larger distances from optical axis and thus encountering much larger absorption.

Supposing that the mirror/lens matches properly, imaging properties should be ruled by imaging properties of the CRL [5]. Either a smaller diameter of condenser or longer focal length is thus needed. If enlarged focal length is used, however, absorption in the air becomes important and has to be taken into account. An example of an image which can be expected if everything goes OK is shown at Figure 1. Expected resolution is therefore \( \sim 1 \mu m \).

![Figure 1. Mesh with 1000 periods per inch imaged by the lens with magnification \( M = 1/5 \). Exposure time is 15 minutes.](image1)

![Figure 2. An example of imaged circular section of the mesh after 5 minutes exposure. The mesh is visible as a shadow at the circle (white arrow). The image is \( 360 \times 260 \mu m^2 \) large.](image2)

5. Conclusions
It has been shown that the Microcapillary lens can be used for imaging in combination with the X-ray tube in both magnifying and demagnifying mode. Further, demonstration of combination of the Micromirror and the Microcapillary lens was shown. It has been demonstrated that mutual optimization of mirror and lens is crucial for future imaging experiments. Currently available elements are not usable for efficient x-ray microscopy imaging.

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