# Hard X-ray Imaging Microscopy using X-ray Guide Tube as Beam Condenser for Field Illumination

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**Abstract**. An optical system for illumination of object in x-ray imaging microscopy is developed. The optical system is a beam condenser consisting of a single-bounce conical-shape mono-capillary (x-ray guide tube: XGT) made of Pyrex glass. The XGT condenser was tested at the beam line 47XU of SPring-8 using a Fresnel zone plate as an objective lens. Comparing with the microscope without beam condenser, the flux density is improved by a factor of 12-20 in the x-ray energy range of 6-8 keV. Test patterns with a 50 nm-structure are clearly resolved at 8 keV with an exposure time less than 1 s.

## 1. Introduction

The illumination optics for imaging microscope is as important as an objective lens. The imaging properties, resolution and contrast, is determined not only by the performance of objective but also by the illumination condition. Off-axis parallel beam illumination is sometimes used in x-ray imaging microscopy with synchrotron radiation x-ray sources. However, the parallel beam illumination is generally improper way for absorption-contrast imaging because of its asymmetric feature and non-uniformity of imaging properties. Although beam diffuser (random phase plate) is often used to improve the imaging properties in off-axis parallel beam illumination, the beam diffuser is also an origin of stray light, which causes reduction of image contrast. A hollow cone illumination is preferable for imaging microscope with Fresnel zone plate (FZP) objective. One of the best illumination optics for the FZP microscope with low-emittance synchrotron radiation light sources is hollow-cone Köhler illumination which was realized with a rotating double-mirror system developed by Niemann et al [1]. We have already developed Köhler illumination system for FZP imaging microscope using concentric periodic-grating optics or combination of linear grating (sector condenser zone plate) [2-4] instead of the rotating double-mirror optics, because the alignment of condenser zone plate is much easier than that of rotating double-mirror system.

The sector condenser zone plate is now usually used for imaging microscopy and microtomography experiments at the beam line 47XU of SPring-8. However, the diffraction efficiency of condenser zone plate is 20-10% in the energy range of 6-12 keV. Improvement of efficiency is one of the most important issues for the microscopy and microtomography experiments. The chromatic aberration of the grating condenser optics is also a disadvantage of diffraction optics. The x-ray guide tube (XGT), a total-reflection-mirror optics consisting of inner surface of tapered glass capillary [5. 6], is a candidate of high-efficiency beam condenser because of high reflectivity of external-total-reflection in the hard x-ray region. We have tried to apply the XGT to an illumination system for FZP microscope. In this report, the design and optical properties of the XGT condenser is described, and the results of performance test at the beam line 47XU of SPring-8 are shown.

## 2. Experimental Setup

The schematic drawing of x-ray imaging microscope optics with the XGT condenser is shown in Fig. 1. The XGT used in the experiment is a single-bounce conical-shape mono-capillary. Some x-ray imaging microscopes operated in the synchrotron radiation facilities are equipped with an axisymmetric total-reflection mirror whose reflecting surface is ellipse of rotation or paraboloid for the condenser system [7, 8]. We chose conical-shape capillary in order to achieve the hollow-cone Köhler illumination. The details of the XGT structure are shown in Fig. 2. The conical-shape tapered-XGT is made of Pyrex glass tube drawn in a furnace under the numerically controlled condition. The XGT usually tend to bend, and the error in straightness was about 0.1 mm or more. In order to correct the bend of XGT, we used a precise V-groove (straightness better than 10 µm), and the XGT is mildly pressed on the V-groove. Hence, the straightness of XGT is estimated to become better than 10 µm. The length of XGT is about 210 mm. The entrance diameter and the exit diameter are 790 µm and 590 mm, respectively. When an illuminating x-ray beam is parallel, the convergent angle of output beam is calculated to be 1.9 mrad from the measured shape of the capillary. The angular divergence of illuminating beam is estimated to be about 10 µrad at the beam line 47XU of SPring-8. Therefore, the parallel beam illumination to the XGT condenser is approximately satisfied.

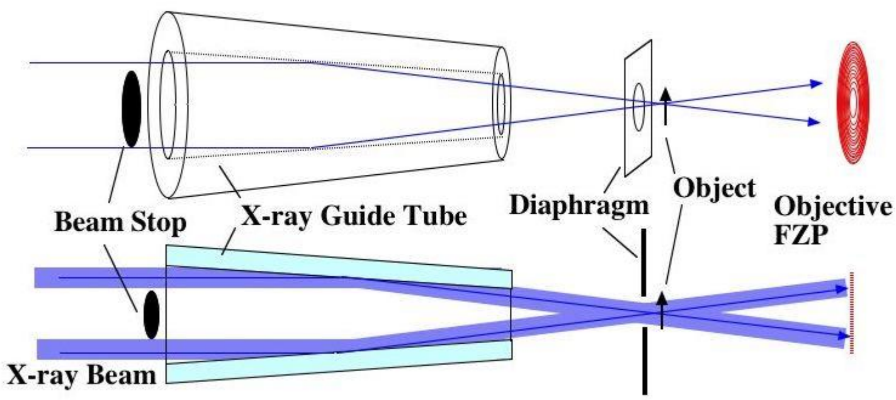


Fig. 1. Schematic diagram of optical system.

A center beam stop made of 0.5 mm-diameter lead ball is placed in front of the XGT condenser in order to stop the direct beam on the object and the objective FZP, and a diaphragm with a diameter of 50 µm is placed in front of the object to define the illuminating field. The hollow-cone Köhler illumination is achieved by using the conical mono-capillary XGT combining with the beam stop and the diaphragm. In the present experiment, the objective zone plate is conventional FZP fabricated at NTT Advanced Technology by electron-beam lithography and reactive ion etching. The zone material is tantalum with a thickness of 0.5 µm. The outermost zone width of FZP is 50 nm, and the diameter is 155 µm. Therefore, the focal length is 50 mm at 8 keV, and 37.5 mm at 6 keV. The numerical aperture (*NA*) is $1.55\text{x}10^{-3}$ at 8 keV, and $2.07\text{x}10^{-3}$ for 6 keV x-rays, respectively. The spatial resolution depends on the convergent angle of illuminating beam. The detection limit for periodic object (grating-like like object) is $\lambda/NA$ in case of normal-incidence parallel-beam illumination, and the best resolution (detection-limit of $0.5\lambda/NA$) is attained for the convergent angle of $2NA$, In contrast, when a convergent angle of illuminating beam is equal to the $NA$ of objective FZP, the maximum field of view is obtained, and the detection limit for periodic object becomes $2\lambda/(3NA)$ in the full-pitch periodic length. The convergent angle of the XGT condenser, 1.9 mrad, is matched with the numerical aperture of the used FZP to optimize the field of view at the x-ray energy region of 6-8 keV. The object and field-defining diaphragm are placed about 320 mm from the middle point of XGT.

The x-ray microscope setup in this experiment is essentially the same as that of our previous experiment except for the XGT condenser system [2-4]. The imaging detector is placed 7 m from the objective FZP. Therefore, the magnification of x-ray optics is about 140 at 8 keV, and 187 at 6 keV. The total length of x-ray microscope is limited by the length of the experimental hutch at the beam line 47XU. The imaging detector is an indirect-sensing-type x-ray camera consisting of a fine-powder phosphor screen (P43: $Gd_2O_2S$: Tb+, 10 µm thick), optical lens system (magnification of about 4), and a cooled charge-coupled-device (CCD) camera. The format of the CCD is 4000 x 2624 pixels, and the pixel size is 5.9 µm. The CCD is operated in a 2 x 2 binning mode. Therefore, the effective pixel of CCD is 2000 x 1312 with a pixel size of 11.8 µm. Then, the convergent pixel size of imaging detector defined by the optical lens system is 3.1 µm, and the effective pixel size in the x-ray microscope is 22.1 nm for 8 keV x-rays, and 16.6 nm for 6 keV x-rays, respectively. The XGT and the FZP were set in a He-flow vessel in order to suppress the contamination and the radiation damage.

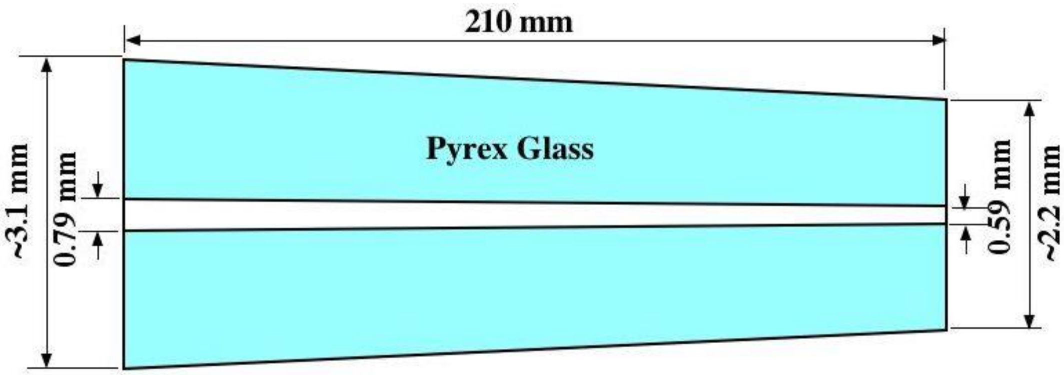


Fig. 2. Structure of conical-shaped XGT. Cross-sectional drawing.

## 3. Results

Fig. 3 shows an example of x-ray microscopy image taken at an x-ray energy of 8 keV with a magnification of about 140. A weak beam diffuser made of a sheet of letter paper is used for suppression of speckle noises. The specimen is resolution test patterns made of tantalum with a thickness of 0.5 µm (x-ray chart: XRESO-50HC, NTT Advanced Technology). The innermost structure of the Siemens star pattern shown in the magnified image of Fig. 3 is 50 nm-line and 50 nm-space. The finest patterns are observable in the measured image as shown in the figure. The exposure time of the image shown in Fig. 3 is 0.7 sec that is about 1/12 of the exposure time without the XGT condenser. Fig. 4 shows an x-ray microscopic image of the same x-ray chart taken at 6 keV. The magnification is 187, and the diffuser is not used in this case. The exposure time is 5 s, which is much longer than that at 8 keV, because of absorption loss by x-ray windows and air. However, the improvement of flux density is about 20, comparing with the exposure time without the XGT condenser. The finest patterns of 50 nm line and space are clearly observable in the measured image. No radiation damages are detected after a continuous 10 hours exposure to the x-ray beam at the beam line 47XU of SPring-8.

The XGT condenser is considered to be very useful for illumination system of full-field imaging microscopy in the hard x-ray region for its high efficiency and achromatic feature.

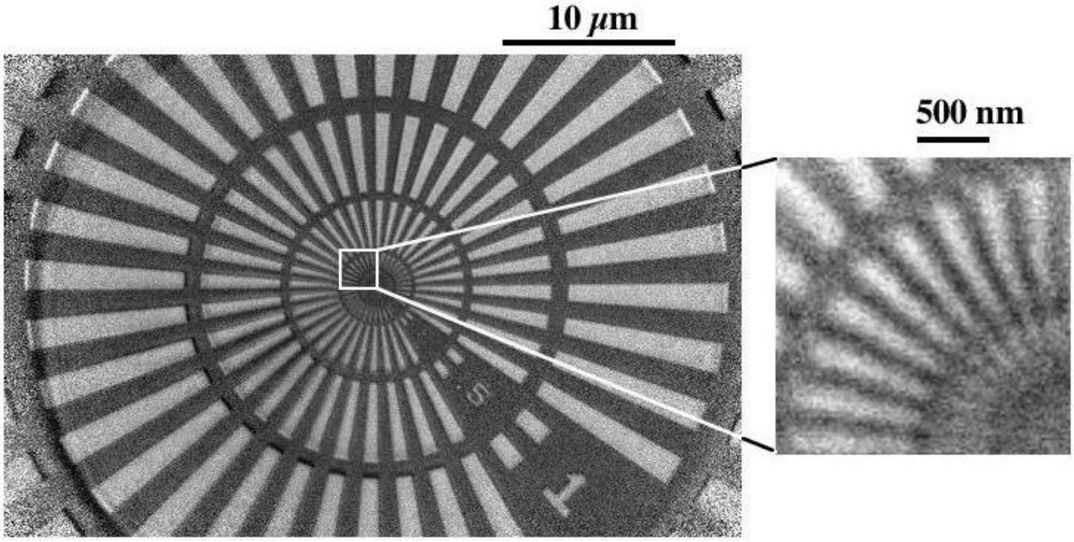


Fig. 3. X-ray microscopy image of resolution test pattern. X-ray energy: 8 keV. Exposure time: 0.7 s.

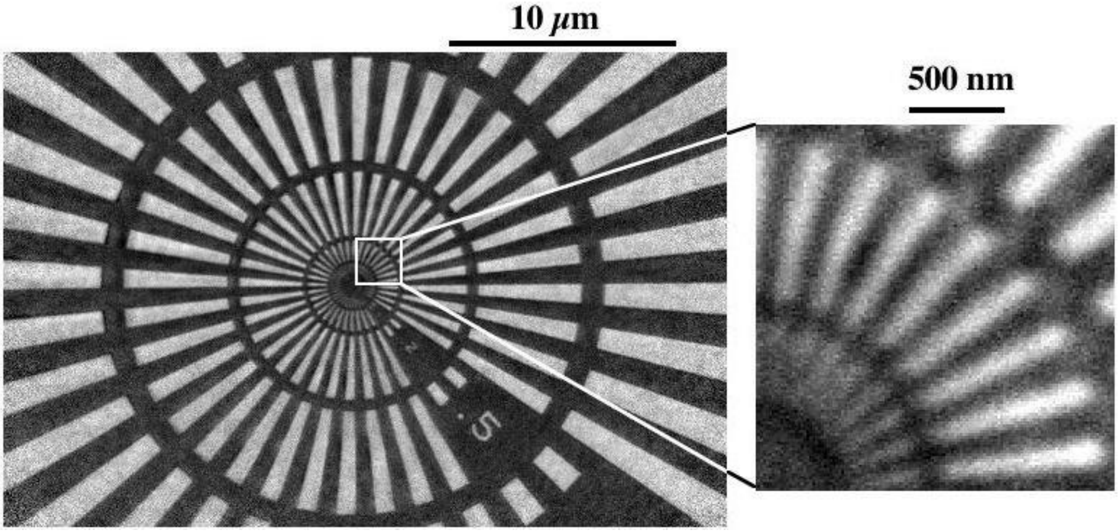


Fig. 4. X-ray microscopy image of test pattern taken at 6 keV. Exposure time is 5 s.

## 4. Acknowledgements
The experiment has been done with an approval of SPring-8 Proposal Review Committee (Proposal No. 2011A1322).

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