

Introducing high efficiency image detector to X-ray imaging tomography

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Abstract. A high efficiency X-ray image detector was introduced in an x-ray imaging micro-tomography system. The detector is a visible light conversion type which consists of phosphor screen, straight-fiber (1:1) optics and scientific CMOS device. The obtained CT images show high reproducibility of X-ray linear absorption coefficient of test material (Cu/Al concentric pattern). The x-ray intensity could be reduced about 10 % of previous system with lens-coupled image detector system.

1. Introduction

An imaging (full-field) X-ray microscope using Fresnel zone plate (FZP) has been developed in some facilities [1-3]. They achieve the spatial resolution of better than 1 micrometer. Increasing the efficiency of objective zone plate and image detector is essential to get better quality of images in x-ray imaging tomography. Those affect scan time, radiation damage on the sample. Concerning the image detector, the signal-to-noise ratio and frame rate are rapidly modified by cutting edge technology such as scientific CMOS (sCMOS) device. The image detector which commonly used in high energy X-ray region is visible light conversion type. The detector consists of phosphor screen, visible light optics and image device. The most used visible light optics (coupling techniques) are lens- and fiber-couplings (fiber optics plate, FOP). The advantage of FOP system is high efficiency (conversion gain) with high numerical aperture optics. In this study, we have introduced FOP-sCMOS detector in the imaging X-ray microscope optics.

2. System

The experiments were carried out at BL47XU in SPRING-8. A schematic illustration of the experimental setup is shown in Figure 1. The developed system consists of an “in-vacuum type” undulator, a Si(111) double crystal monochromator cooled with liquid nitrogen, a double Rh-coated total-reflection mirror system to suppress the higher harmonics, X-ray microscope optics with sector condenser zone plate (sCZP), objective Fresnel zone plate (FZP), Zernike phase plate and an X-ray image detector. The zone material of the sCZP, the FZP, and the Zernike phase plate is tantalum. The parameters are summarized in Table 1. The inner diameter, outer diameter and pattern thickness of the Zernike phase plate are 151 μm , 159 μm and 0.96 μm , respectively. High precision stages are made by Kohzu precision Co., Ltd. All automatic translation stages have accuracy better than 1 μm . The sample rotation stage (RD55-01) has been specially developed for high load capacity. The effective pixel size at 8 keV is about 90 nm/pixel. The detail of the X-ray microscope optics was described in elsewhere [4-6].



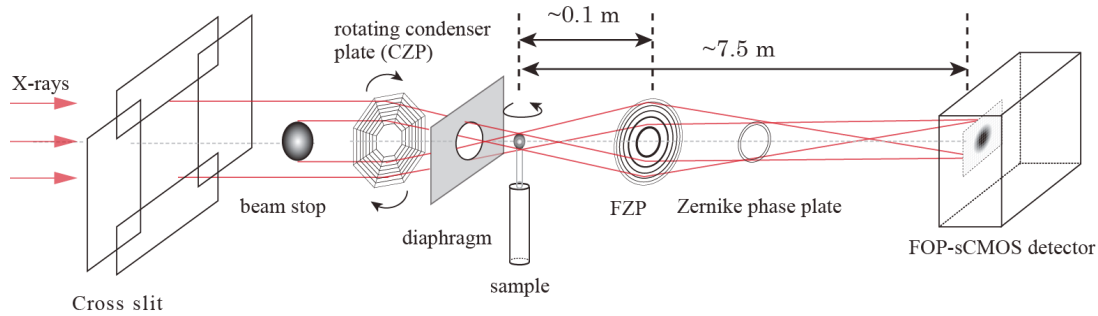


Figure 1. A schematic illustration of the system. Light source, double crystal monochromator and total reflection mirrors are not shown.

TABLE 1. Parameters of CZP and FZP. Both zone plates are made of Tantalum on SiC membrane (2 μ m-thickness). The ZPs were fabricated by means of the electron-beam lithography technique at NTT-AT, Japan.*This number shows the distance from CZP to sample which has some uncertainty because of the size of beam stop in front of the CZP.

	CZP (sector type)	FZP
Number of zones	2250	1550
Diameter (μ m)	1000	310.0
Outermost zone width (nm)	100	50
Focal length at 8keV (mm)	*400	100
Thickness of zones (μ m)	1.0	1.0

2.1. X-ray image detector

We have tested some detectors to fit the X-ray full field microscope optics. The specifications of detectors for imaging microscope were measured at experimental hutch 1 of BL20B2 in SPring-8 using 10keV X-ray, which is summarized in Table 2. All of the experiments were done under the “photon limited condition”, therefore the S/N of the images was determined by the number of X-ray photon. Type (a), (b) and (c) has same sCMOS chip (FL-400, Hamamatsu Photonics) inside. Phosphor screen and sCMOS chip are connected by 1:1 fiber optics plate in type (a) and (b). Type (c) consists of a phosphor screen (P43 10 μ m-thickness), a tandem lens system of two camera lens (two AI AF Nikkor 50mm f/1.4D) and sCMOS camera (C11440-22C, Hamamatsu Photonics). All of them have the magnification factor of one. Therefore, the effective pixel sizes are the same as pixel size of sCMOS chip. The type (a) has highest conversion gain and the highest modulation transfer function (MTF) (Figure 2). Therefore the type (a) detector (Hamamatsu Photonics, C12849-1015S) was used in this study.

Table 2. Characteristics of each detector.

	(a)	(b)	(c)
Optics type	FOP	FOP	Lens
Phosphor	Gd ₂ O ₂ S:Tb ⁺	CsI:Tl ⁺	Gd ₂ O ₂ S:Tb ⁺
Thickness (μ m)	10	50	10
Exposure (msec)	20	10	60
Pixel size (μ m)	6.5 x 6.5	6.5 x 6.5	6.5 x 6.5
Format	2048 x 2048	2048 x 2048	2048 x 2048
Frame rate (Hz)	30	30	100
Conversion gain (e-/photon)	22.5	20.2	3.5

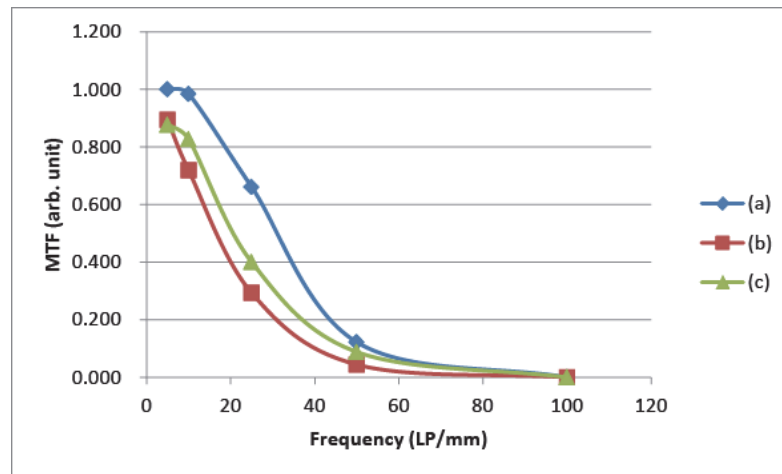


Figure 2. Modulation transfer function (MTF) of each detector summarized in Table 2. The MTF was measured at BL20B2 of SPring-8 using 10keV energy X-ray.

3. Results

3.1. Evaluation of the system

For the evaluation of the spatial resolution and quantitative properties of the X-ray linear absorption coefficient (LAC) measured by tomography, the artificial test patterns of Aluminium (Al) and copper (Cu) multilayer were fabricated at AIST Kansai [7,8]. Cu and Al were deposited onto rotating Al wire substrate by DC magnetron sputtering apparatus.

300 nm pitches of Al and Cu (Each line width is 150 nm.) are clearly resolved. It shows that the spatial resolution is higher than 300 nm. Potentially it would be around 200 nm because the spatial resolution (5% MTF) of the image detector is 2.2 pixels (197 nm in this case) and wobble of the rotation stage (Kohzu precision RD55-01) is less than 100nm.

As shown in Figure 2, FOP system has better MTF than lens system with the same phosphor screen. The line profiles of CT images also show the same result (Figure 3 (c)).

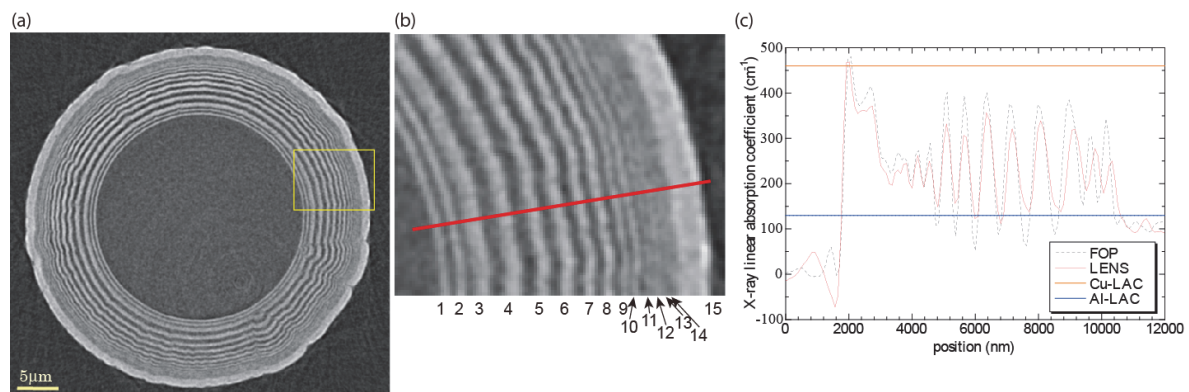


Figure 3. (a, b) CT image of multilayer test pattern using FOP-sCMOS. (b) The numbers show the thickness of Cu layer. 1,2: 250 nm, 3,4:500 nm, 5,6:400 nm, 7,8:300 nm, 9,10:200 nm, 11,12,13,14:150 nm, 15:1000 nm. (c) Line profiles of test pattern using lens-coupled and FOP detectors. Energy:8 keV, Pixel size:89.7 nm/pixel, Field of view:φ115 μm, Exposure time:250 msec/projection, Number of projection:900.

3.2. Demonstration

As a demonstration, a proturan head was imaged with the developed system. The proturan was fixed and dehydrate with Bouin Solution and ethanol, respectively. Although the scan time was only 15

minutes, the image could not obtain using Lens-coupled detector system because of the deformation of the sample during the scan. The proturan head was successfully observed by changing the system from lens-coupled detector to FOP detector. The X-ray intensity was reduced to 10% of lens-coupled detector and the scan time was reduced to 5 minutes. Therefore the total dose was reduced to approximately 3% of the Lens-coupled detector system's.

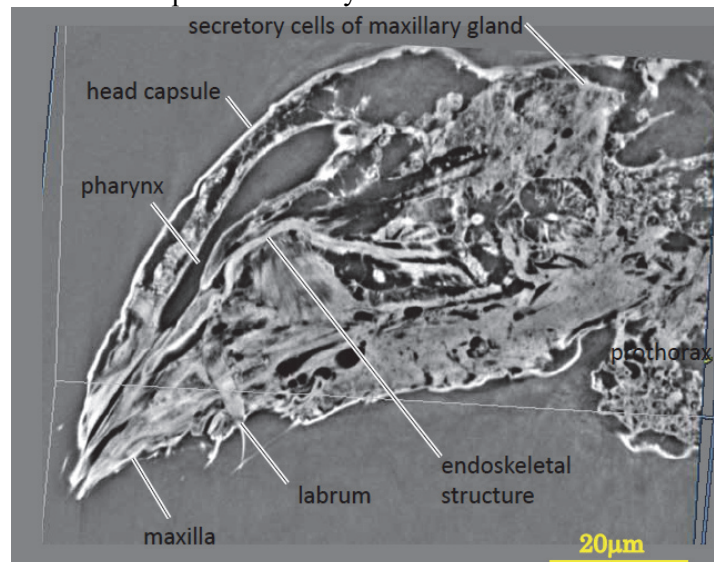


Figure 4. A sagittal view of the proturan head. Energy:8 keV, Pixel size:91.9 nm/pixel, Field of view: ϕ 115 μ m, Exposure time:250 msec/projection, Number of projection:900. Zernike phase plate was used to obtain phase contrast images.

4. Summary

Incident X-ray intensity has been reduced to 1/10 of previous system using high efficiency X-ray image detector (FOP-sCMOS) in X-ray imaging (full-field) microscope, which is essential for avoiding radiation damage on the samples. Furthermore the scan time is only 5 minutes for 900 projections. The sample deformation and drift of imaging optics could be negligible small during the short scan time. The spatial resolution is 200 nm in this case.

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