Fresnel zone plate with apodized aperture for hard X-ray Gaussian beam optics

X-ray tomographic microscopy is a high spatial resolution three-dimensional (3D) computed tomography (CT) system using an X-ray full-field microscope optics. This system is called a nano-CT system because of its spatial resolution of from several tens to several hundreds of nanometers whereas the spatial resolution of a micro-CT system using a simple projection optics is limited to around 1 μm. X-ray nano-CT system using a Fresnel zone plate (FZP) as an objective are now open for user experiments at SPring-8 **BL37XU** and **BL47XU**, and are used in various fields such as materials, minerals, space/earth science, industrial use, and batteries.

An FZP is known as an approximately off-axis-aberration-free optics in the hard X-ray region [1]. However, it has been pointed out that some kinds of noises such as periodic fringes, edge enhancement, and streak noise tend to occur, particularly in the peripheral region of the field of view. Figure 1(a) shows an example of nano-CT measurement. Edge enhancement and contrast unevenness due to streak noise, which are severe obstacles to quantitative measurement, are observed in the CT image.

The reason for this is as follows. An image obtained with a full-field microscope optical system is expressed by the convolution of the transmittance function of the object and the point spread function (PSF) of the optical system. Here, the pupil function of the objective and the PSF are related by a Fourier transform. In general, since the objective has a circular or rectangular aperture, its PSF is expressed as a Bessel function or a Sinc function, respectively. These functions are known as having ripples (multiple side peaks) around the main peak that cause periodic noise called ringing. Although ringing is generally inconspicuous in the paraxial region corresponding to the central region of the field of view, it becomes more conspicuous in the off-axis region corresponding to the periphery of the field of view. Therefore, even if an ideal aberration-free lens is used, these noises are generated because of its finite aperture. Furthermore, since the ringing contains the phase information of the object, large contrast noise is generated even with a small absorption object.

These noises can be effectively reduced by introducing a Gaussian beam optical system, whose electric field or intensity distribution can be regarded as approximately Gaussian. Therefore, its Fourier plane also has a Gaussian profile. Gaussian beam optics has some advantages such as (i) they are easy to handle mathematically, (ii) it is possible to remove high frequency speckle and fringe noises, and (iii) it is not necessary to set clear boundary conditions for the object. In recent years, several techniques for Gaussian beam optics in the X-ray region have been proposed [2,3]. In the case of a full-field microscope optical system, both the pupil function of the objective and the PSF are represented by their Gaussians. Since a Gaussian beam does not have ripples, no fringe noise is observed in the image. To convert a general objective aperture having a clear boundary into one with an ambiguous boundary, it is effective to install a filter whose transmittance gradually decreases from the central region to the peripheral region. This method of reducing the ripples by multiplying by an appropriate filter at the Fourier space is called apodization. An FZP with an apodization function (apodization FZP, A-FZP) was developed for introducing a Gaussian beam optical system into the optical system of an X-ray nano-CT system [4].

The aperture function of the FZP optics can be expressed as the first-order diffraction efficiency distribution. In the hard X-ray region, the zone depth is related to the diffraction efficiency distribution. In the case of a conventional FZP, which has a uniform zone depth, therefore, it has a pupil function defined as a definite circle or rectangle as shown in Fig. 2(a). On the other hand, as shown in Fig. 2(b), when an FZP has a structure in which the zone thickness decreases toward the periphery, the diffraction efficiency

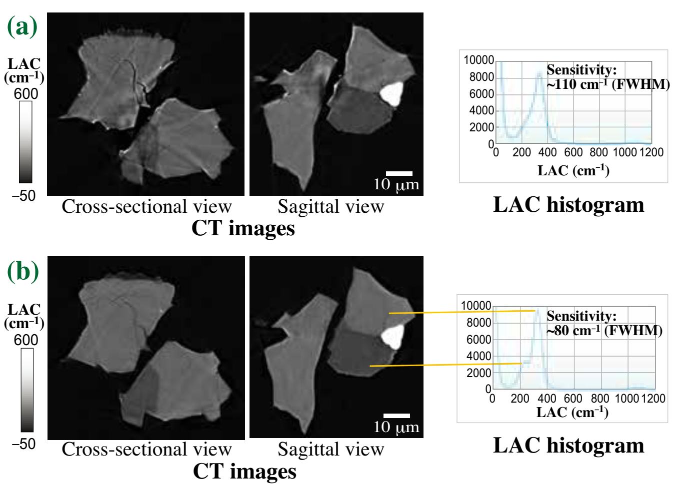

Fig. 1. Nano-CT images and CT value histograms of a Kilabo meteorite measured **(a)** by using a conventional FZP and **(b)** by using an apodization FZP as the objective. X-ray energy is 8 keV, voxel size is 83.7 nm, exposure time is 0.5 s, and CT scan time is 30 min for 1800 images/180 deg.

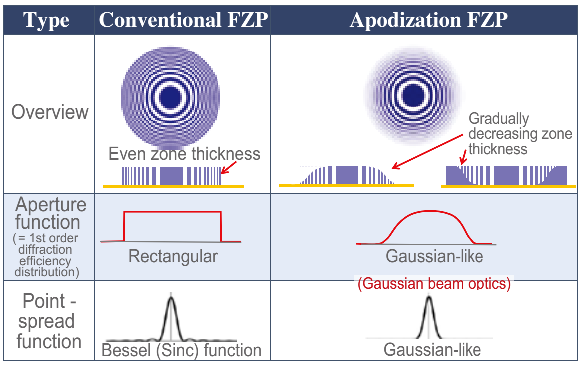

Fig. 2. Schematic drawings of conventional FZP (left) and A-FZP (right). A-FZP has a gradually decreasing zone thickness from the central region to the peripheral region, whereas conventional FZP has an even zone structure (upper). A-FZP has a Gaussian-like aperture function (middle) and also has a Gaussian-like PSF (lower), realizing a Gaussian beam optics.

gradually decreases in the peripheral region. This naturally realizes an FZP with an apodized aperture. Such a zone structure, which seems to be difficult to fabricate, however, it is not so difficult to realize. For a dry-etching process, which is one of the manufacturing processes used in the fabrication of FZPs by electron-beam lithography, it is known that the etching depth decreases with the patterns width. Such a phenomenon is called the microloading effect [5]. So far, this effect has been very problematic in fabricating an FZP having a uniform zone depth. Fortunately, however, it is a very convenient effect in fabricating an A-FZP. In other words, the zone structure that was previously recognized as a poorly finished FZP was actually an excellent A-FZP.

By actively employing the microloading effect, an A-FZP with an outermost zone width of 50 nm was fabricated by NTT Advanced Technology. Figure 3 shows the focal beam profile measured by a microbeam knife-edge scan as a performance test. The measured spot size was 55 nm in full width at the half maximum (FWHM), representing the nearly diffraction-limited resolution. This profile, in which ripples are considerably suppressed compared with the theoretical value for the conventional focus, has a shape resembling a Gaussian. An example of measurement using the nano-CT system with this A-FZP as an objective is shown in Fig. 1(b). The measured sample is the same as that of Fig. 1(a) measured with a conventional FZP. Edge enhancement, streak noise, and contrast unevenness, as can be seen in Fig. 1(a), are considerably suppressed in Fig. 1(b). Comparing the histograms of the linear absorption coefficient (LAC), Fig. 1(a) shows a single broad peak, whereas Fig. 1(b) clearly shows two separate peaks in the histogram. These results show that the introduction of a Gaussian beam realizes marked noise suppression and enables more quantitative and sensitive measurement.

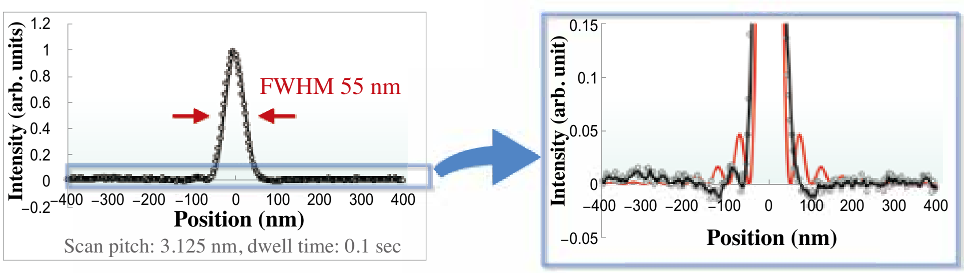

Fig. 3. Focused beam profile of A-FZP (with outermost zone width of 50 nm) measured by microbeam knife-edge scan (left) and magnified view of the bottom region of the profile (right). X-ray energy is 8 keV. Measured spot size was 55 nm, corresponding to the nearly diffraction-limited resolution of the FZP with an outermost zone width of 50 nm. Red line in the right view shows the theoretical value of the PSF of the conventional FZP. Measured value shows that the ripples were considerably suppressed compared with the red line.

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