Super-resolution x-ray imaging using interaction between periodic structure of object and standing wave generated with total-reflection-mirror interferometer

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Abstract. A super-resolution method in projection-type x-ray imaging is proposed. In this method, interference fringes generated with a two-beam interferometer are used for detecting the fine periodic structure of the object. When the sample has a fine periodic structure, the structure can be detected as interaction between the periodic structure of object and the standing wave formed by the two-beam interferometer. Feasibility studies have been carried out using wavefront-division interferometer with total-reflection-mirror optics and a resolution test chart as a model sample. The fine structures with a period up to 100 nm were detected as modulation of transmitting x-ray intensity at 11.5 keV.

1. Introduction

Spatial resolution of projection-type imaging in the x-ray region is generally limited by the spatial resolution of the imaging detector. Owing to the technical limitations, the spatial resolution of x-ray imaging detector is presently limited to around 1 μm. The higher spatial resolution is, of course, achievable by using x-ray image-forming optics such as Fresnel zone plate, total reflection mirrors, and compound refractive lens. However, the fabrication of high-resolution optical elements for hard x-rays is still a difficult task at present.

Recently, we have proposed a method for overcoming the spatial resolution limit in the x-ray projection imaging, in which interaction between periodic structure of object and a standing wave generated by a two-beam interferometer is used [1]. The fine periodic structures beyond the spatial resolution of imaging system can be detected as modulation of transmitting beam intensity. This method is a kind of super resolution, i.e. spatial resolution beyond the resolution limit of imaging system. Many types of optical systems for two-beam interferometer have ever been developed in the x-ray region: Fresnel biprism optics for hard x-rays [2, 3], total-reflection-mirror system for soft x-rays [4], mono-prism optics [5], total-reflection-mirror system for hard x-rays [6], and bilens optics [7]. In our previous experiment, a two-beam interferometer with single prism optics, which is an analogue of Fresnel's biprism optics in the visible light region, was used for generation of periodic standing wave, and it was confirmed that the fine periodic structures can be detected as the modulation of transmitting beam intensity as well as the modulation of fluorescent x-ray yield.

However, in our previous experiment, there is a problem due to the absorption loss at the prism. It is difficult to produce uniform fine periodic fringes in a wide field of view, and it is also difficult to apply it to soft x-rays. In the present experiment, a total-reflection-mirror interferometer is used instead of the refractive prism, and a standing wave with a period up to 100 nm can be generated. The feasibility study for super-resolution imaging is carried out using a resolution test pattern having fine periodic structures as a model object.

2. Experimental setup

The principle of interaction between x-ray interference fringes and object is schematically shown in Fig. 1. When two parallel waves are crossed on the object plane, a sinusoidal periodic field is generated by the interference between two plane waves. The period, d, of the standing wave is expressed as $d = \lambda /(2\sin(\phi /2)$, where λ is wavelength of x-ray and ϕ is intersecting angle between two beams. The d is approximately rewritten as $d \sim \lambda/\phi$ for small ϕ. When an object having a periodic structure is placed in the standing wave field, modulation in intensity of transmitting beam, corresponding to the interaction between the periodic structure of specimen and the standing wave, is observed by scanning the interference fringe position.

The maximum modulation in the transmitting beam intensity is observed when the period of the structure in the object is equal to the interference fringe pitch. If the fringe period is slightly mismatched with the object structure, a moiré pattern is observed in the measured projection image. Thus, the existence of fine periodic structures can be detected as a modulation of transmitting beam intensity that is independent on the spatial resolution of the imaging detector.

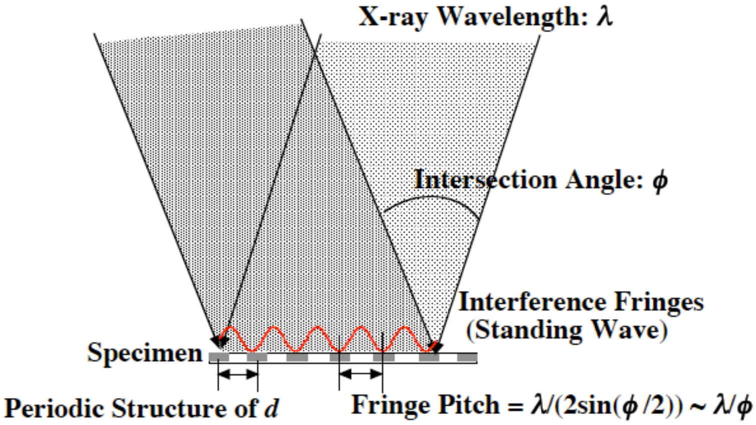

Figure 1. Schematic diagram of standing wave generated with two-beam interferometer and its interaction with periodic structure of object

The experiments have been performed at the BL20XU of SPring-8 [8]. Schematic diagram of experimental setup is shown in Fig. 2. The undulator radiation from 173-pole planar undulator is monochromatized by passing through a liquid-nitrogen-cooling Si 111 double-crystal monochromator. As shown in the figure, the coherent intersecting beam can be generated by a wavefront-division interferometer with a plane total-reflection mirror, i.e. Lloyd's mirror configuration with plane wave illumination. A part of plane wave is deflected by the total-reflection mirror and superimposed on the direct beam. The standing wave is generated in the beam-overlapping area. The deflection angle can be changed by the glancing angle to the mirror. The plane mirror used in the experiment is 150 mm-long Pyrex mirror without any surface coating. The surface figure accuracy of the mirror is better than $\lambda/10$ for He-Ne laser wavelength (632.8 nm). The spatial coherence of incoming wave is defined by a slit placed at about 196 m from the interferometer. In the present experiment, the spatial coherence is required only in the vertical direction, because the vertical beam deflection geometry is employed. Therefore, the coherence is defined only in the vertical direction with a slit of a width of 10 μm. Therefore, the spatial coherence area defined by the fringe visibility of 0.88 is calculated to be larger than 0.5 mm at an x-ray wavelength of 1 Å. The object is placed at about 20 mm from the rear end of the mirror.

A resolution test chart (XRESO-50HC, NTT-AT) is used as a model sample of periodic structures. The test chart made of 0.5 μm-thick-tantalum has stripe patterns whose periods are 200 nm and 100 nm, respectively. A negative pattern is drawn in a square region of 19.5 μm x 19.5 μm. Transmission image of object is measured by an indirect sensing x-ray camera consisting of a phosphor screen (20 μm-thick single crystal of $Lu_2SiO_3:Ce^+$), optical lens system, and a cooled CMOS image sensor. The effective pixel size of the detector is 0.244 μm, and the distance from object and imaging detector is about 2 mm. X-ray energy of 11.5 keV (wavelength of 1.078 Å) is chosen in the experiment to maximize the absorption contrast of the test pattern made of Ta.

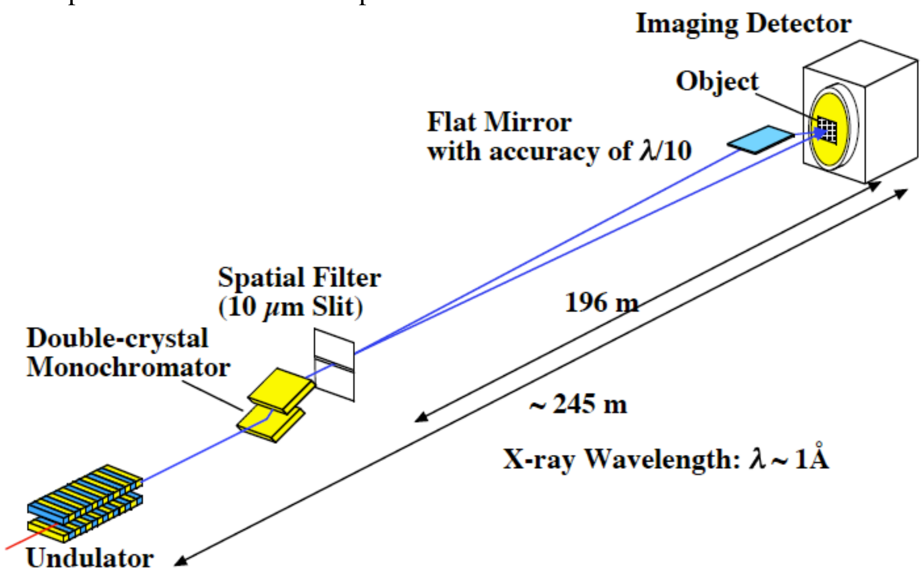

Figure 2. Schematic diagram of experimental setup at BL20XU of SPring-8.

3. Results and Discussions

Typical transmission images measured at an intersecting angle that is slightly (0.02 mrad) detuned from the optimum angle are shown in Fig. 3. Clear moirê fringes of about 4 periods (5 μm pitch) are visible both in the 200 nm-period pattern image (Fig. 3a) and in the 100 nm-period pattern image (Fig. 3b). The quantitative measurements have been performed by means of scanning the position of the standing wave. The sequential images were acquired by step-by-step translational scan of the mirror position. The qualitative intensity modulation by fringe scan of standing wave is shown in Fig. 4. Here, the beam intensity is integrated in a 20 μm x 20 μm square region of the periodic patterns. Clear sinusoidal modulation with a period of 200 nm is observed in the transmitting beam intensity as shown in Fig. 4a. The 100 nm-period pattern is also measured by the similar manor. The result is shown in Fig. 4b. The sinusoidal intensity modulation with a period of 100 nm is also clearly observed.

The exact periodic length of standing wave can be determined by the intersection angle of two plane waves that can be measured by far-field image combining with a spatial pinhole placed in front of the object [1]. The measured pitches are 199.3 nm and 100.8 nm for the 200 nm-pattern and 100 nm-pattern, respectively. As a result, it is confirmed that nanometer periodic structures can be detected by the standing-wave super-resolution technique with the total-reflection-mirror interferometer, and the quantitative measurement of periodic length is also capable.

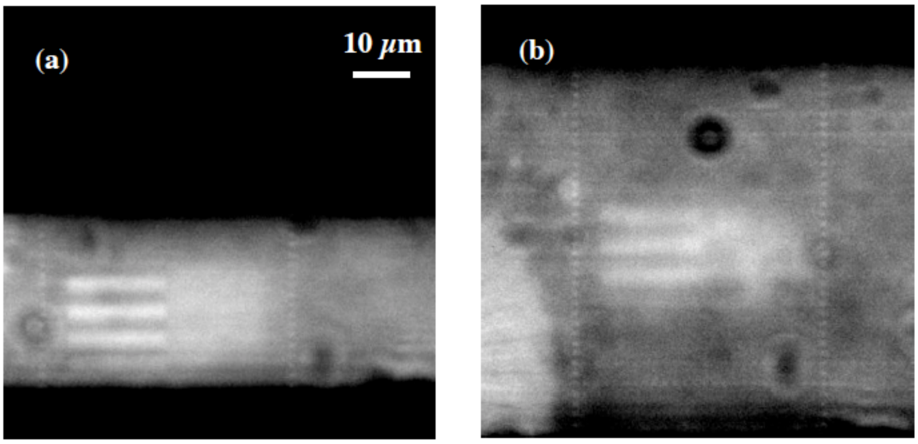

Figure 3. Transmission image of resolution test patter with standing wave illumination. (a) Line and space patterns with a period of 200 nm at ϕ = 0.522 mrad (offset angle of 0.02 mrad). (b) 100 nm-period patterns at ϕ = 1.086 mrad (offset angle of 0.02 mrad). X-ray energy is 11.5 keV (1.078 Å). Exposure time is 10 s.

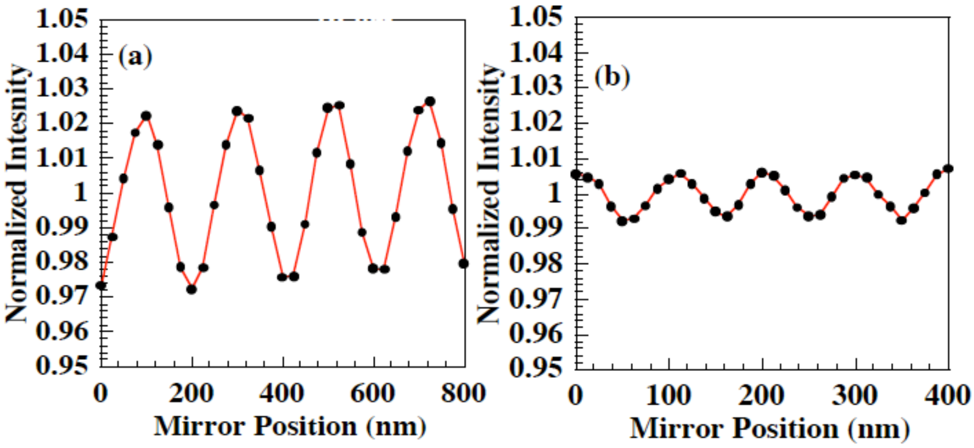

Figure 4. Transmission Fringe scan results for (a) 200 nm-period pattern and (b) 100 nm-period pattern. X-ray energy of 11.5 keV (1.078 Å). Solid circles are measured data. Integration time for each point is 10 s.

4. Acknowledgement

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References

[1] Y. Suzuki, Rev. Sci. Instrum. **86**, 043701 (2015).
[2] A. R. Lang and A. P. W. Makepeace, J. Synchrotron Radiat. **6**, 59 (1999).
[3] A. F. Isakovic, A. Stein, J. B. Warren, A. R. Sandy, S. Narayanan, M. Sprung, J. M. Ablett, D. P. Siddons, M. Metzlerc, and K. Evans-Lutterod, J. Synchrotron Radiat. **17**, 451 (2010).
[4] W. Cash, A. Shipley, S. Osterman, and M. Joy, Nature **407**, 160 (2000).
[5] Y. Suzuki, Jpn. J. Appl. Phys. **41**, L1019 (2002).
[6] Y. Suzuki and A. Takeuchi, Jpn. J. Appl. Phys. **47**, 8595 (2008).
[7] A. Snigirev, I. Snigireva, V. Kohn, V. Yunkin, S. Kuznetsov, M. B. Grigoriev, T. Roth, G. Vaughan, and C. Detlefs, Phys. Rev. Lett. **103**, 064801 (2009).
[8] Y. Suzuki, et al, AIP Conf. Proc. **705**, 344 (2004).