Nuclear Instruments and Methods in Physics Research A 619 (2010) 319–322

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Analysis of partial coherence in grating-based phase-contrast X-ray imaging

Zhili Wang [a], Xiaosong Liu [a], Peiping Zhu [a,**], Wanxia Huang [a], Qingxi Yuan [a], Enrong Li [a], Yijin Liu [b], Kai Zhang [a], Youli Hong [a], Ziyu Wu [a,b,c,*]

[a] Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China
[b] National Synchrotron Radiation Laboratory, University of Science and Technology of China, Hefei 230026, China
[c] Theoretical Physics Center for Science Facilities, Chinese Academy of Sciences, Beijing 100049, China

ARTICLE INFO

Available online 28 October 2009

Keywords:
Partial coherence
Self-image
Fractional Talbot distance
Visibility

ABSTRACT

We report here a quantitative analysis of the effect of partial coherence on grating-based phase-contrast X-ray imaging. The self-image intensity has been derived through the phase-space formulation in the framework of the Wigner distribution. Based on the behavior of the self-image visibility, the minimum required spatial coherence length is given for three different types of gratings. Furthermore, we show that the coherence requirement, at different fractional Talbot distances, increases linearly with the Talbot order for the three types of gratings. The approach we presented can also be successfully applied to the Talbot–Lau geometry.

1. Introduction

The sensitivity of conventional hard X-ray imaging is often not sufficient to perform detailed internal observations of samples consisting of low-Z elements because of the weak absorption. Phase-contrast X-ray imaging, which uses the phase shift as image contrast, provides a way of performing detailed observations of samples with an improved sensitivity [1–3]. Several hard X-ray phase-contrast imaging methods have been developed since the 1990s. They can be categorized into interferometric imaging [4,5], propagation-based imaging [6,7], analyzer-based imaging [8–11] (also called diffraction enhanced imaging) and grating-based differential phase-contrast imaging (DPC) [12–17]. Among them, DPC with hard X-rays offers great advantages over existing X-ray phase-contrast methods: firstly, the potential to realize fields of viewing large and, secondly, the possibility to efficiently use curved wavefronts and polychromatic sources of low-brilliance [14,17]. When combined with a tomographic scan, it makes possible the three-dimensional reconstruction of the distribution of X-ray refractive index of the sample, as well as the distribution of absorption coefficient commonly obtained in the absorption-based tomography methods [16].

Weitkamp et al. [13] have discussed the minimum required transverse coherence length in the case of π phase modulation. Based on the behavior of visibilities of the self-image, Momose et al. [15] have presented the corresponding results in the case of $\pi/2$ phase modulation. Nesterets and Wilkins [18] also presented simulation results on the effect of source size in a scanning-double-grating configuration. However, no quantitative analysis of partial coherence in DPCI has been reported yet, and in this communication we present our results for three different types of gratings. The work is based on the expression for the self-image intensity under partially coherent illumination, which has been derived through phase-space formulation using the Wigner distribution [19,20]. We show that the partial coherence effects of incident X-ray wave on the self-image can be simply accounted for as a multiplication factor. In this article, we particularly discuss the minimum required spatial coherence length for efficient operation of DPC with three different types of gratings. For different fractional Talbot distances, the coherence requirement is almost proportional to the Talbot order. The analysis is also valid for the Talbot–Lau geometry.

2. Methods

As schematically shown in Fig. 1, the essential DPC setup consists of the first grating G1, the second absorption grating G2 and an image detector [15]. The distance between the gratings is set to be one of the fractional Talbot distances of G1, denoted by D_m, so that the fractional Talbot effect by G1 occurs at the position of G2; i.e., a self-image with a period corresponding to the pitch of G1 is formed on G2. When a sample is placed immediately in front of the grating G1, the self-image is deformed owing to the refraction at the sample. The analyzer absorption grating G2 transforms the deformation into intensity variation recorded by

* Corresponding author at:. National Synchrotron Radiation Laboratory, University of Science and Technology of China, Hefei 230026, China,.
Tel.: +86 010 88236478; fax: +86 010 88236229.
** Also corresponding author.
E-mail addresses: zhupp@mail.ihep.ac.cn (P. Zhu), wuzy@ustc.edu.cn (Z. Wu).

0168-9002/$ - see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.nima.2009.10.126

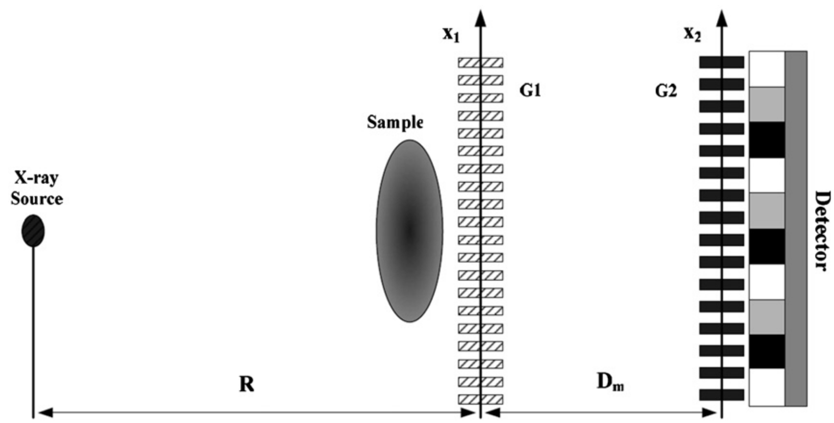

Fig. 1. Schematic representation of grating-based phase-contrast imaging setup. G1 is a phase grating or an amplitude grating while G2 must be an absorption grating. Both gratings have a duty cycle of 0.5.

the image detector. Here, the X-ray optical axis is parallel to the z axis, and the line pattern of the gratings is parallel to the y axis.

Under partially coherent illumination with a normalized unitary intensity, the intensity of the self-image formed by the grating G1 has the following form:

$$I(x_2, D_m) = \sum_n c_n \mu_{in}\left(\frac{\lambda D_m n}{Md/\eta}\right) \exp\left[2\pi i \frac{n x_2}{Md/\eta}\right] \tag{1}$$

where λ is the X-ray wavelength, c_n the Fourier coefficient determined by the grating G1, $M=(R+D_m)/R$ the magnification factor, and R the curvature radius of the incident X-ray wave.

As illustrated in Fig. 1, the fractional Talbot distances, i.e., the positions along the optical axis at which the self-image pattern exhibits a maximum modulation, are, for an incident spherical wave [21],

$$D_m = \frac{Rmd^2}{2\eta^2 \lambda R - md^2} \quad (m = 1, 2, 3, \ldots) \tag{2}$$

where d is the period of the first grating G1. The integer number m, called the Talbot order, is odd for a phase grating and even for an amplitude grating. The factor η, depending on the optical properties of the grating G1, satisfies

$$\eta = \begin{cases} 1 & \text{if G1 is a } \pi/2 \text{ phase grating or an amplitude grating} \\ 2 & \text{if G1 is a } \pi \text{ phase grating} \end{cases} \tag{3}$$

For partially coherent illumination, let us consider the generalized Gaussian-Schell-model sources [20], for which the complex degree of coherence of the incident X-rays $\mu_{in}(\lambda D_m n/Md/\eta)$ is given by the van Cittert-Zernike theorem as [22]

$$\mu_{in}\left(\frac{\lambda D_m n}{Md/\eta}\right) = \exp\left[-\frac{1}{8}\left(\frac{md}{\eta L}\right)^2 n^2\right] \tag{4}$$

where L denotes the spatial coherence length, which is defined by [15]

$$L = \frac{\lambda R}{2\pi\sigma_x} \tag{5}$$

where σ_x denotes the RMS of the intensity distribution in the source plane. Substituting Eq. (5) into Eq. (1), we obtain

$$I(x_2, D_m) = \sum_n c_n \exp\left[-\frac{1}{8}\left(\frac{md}{\eta L}\right)^2 n^2\right] \exp\left[2\pi i \frac{n x_2}{Md/\eta}\right] \tag{6}$$

As can be seen from Eq. (6), it is the ratio $md/\eta L$ that determines the partial coherence effects on the self-image. Based on Eq. (6), we can conclude that the minimum required spatial coherence lengths for efficient operation of DPC with different types of gratings are different, and that the coherence requirement at different distances is related to the Talbot order m. In the next section, numerical simulations will help us to clearly demonstrate the influence of partial coherence on DPC.

3. Numerical results

The visibility of the self-image is the most important figure of merit for the efficiency of DPC, which is defined as $V \equiv (I_{\max} - I_{\min})/(I_{\max} + I_{\min})$ with $I_{\max}$ and $I_{\min}$ being correspondingly the maximum and minimum intensity values in the self-image. In this section, we discuss the coherence requirements for different types of gratings to obtain the self-image with a high visibility. The following numerical simulations have been carried out to provide a quantitative insight into the problem of the effect of partial coherent illumination on the self-image visibility. The period d of the first grating is 4 μm. The corresponding fractional Talbot distance can be calculated using Eq. (2).

The visibilities of the self-images for different types of gratings at their various fractional Talbot distances plotted as a function of L/d are shown in Fig. 2. As shown in Fig. 2(a), for a π phase grating, a self-image with a visibility of greater than 0.7 is produced when the spatial coherence length is larger than one-fourth of the grating period. It is noteworthy that even when $L/d=0.2$, a visibility of ~0.6 is obtained. Experiments have demonstrated that a visibility greater than 0.2 is sufficient for phase imaging provided the pattern of the grating G2 is sufficiently thick [23]. Taking the noise in experimental applications into account, here we choose the visibility of 0.6 as a criterion for further analysis of the coherence requirements. According to the criterion, the coherence requirements for three types of gratings at different Talbot orders are summarized in Table 1 below.

The following two practically important trends can be established by analysis of Fig. 2 and the data in Table 1. First, the minimum required coherence length is different for different types of gratings. For the π phase grating, the requirement is one-fifth of the grating period. The corresponding results are two-fifths for the $\pi/2$ phase grating, and four-fifths for the amplitude grating. The various requirements can be attributed to the differences in the minimum fractional Talbot distance, which results in different spatial separations of the interference beams. In the case of a π phase grating, the self-image is mainly a constructive interference between the +1st and −1st orders. The two beams are spatially separated by $2\lambda D_m/d = md/4$, in the case of the first fractional Talbot distance one-fourth of the grating