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Numerical design of X-ray tabletop Talbot interferometer using polycapillary optics as two-dimensional gratings with high aspect ratio

Weiyuan Sun [a,b,c], Zhiguo Liu [a,b,c], Tianxi Sun [a,b,c,*], Xuepeng Sun [a,b,c], Fangzuo Li [a,b,c], Bowen Jiang [a,b,c], Xunliang Ding [a,b,c]

[a] The Key Laboratory of Beam Technology and Material Modification of Ministry of Education, Beijing Normal University, Beijing 100875, PR China
[b] College of Nuclear Science and Technology, Beijing Normal University, Beijing 100875, PR China
[c] Beijing Radiation Center, Beijing 100875, PR China

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ABSTRACT

The polycapillary optics was proposed to be used as two-dimensional X-ray gratings with high aspect ratios for high energy X-rays. The X-ray Talbot interferometer was designed numerically using the polycapillary X-ray gratings and a conventional X-ray source. The simulation showed that it was available to get a high-aspect-ratio pattern of the polycapillary X-ray gratings for higher energies than 60 keV. Moreover, this design of polycapillary gratings decreased the requirement for high power of the X-ray source. The polycapillary X-ray gratings had potential applications in X-ray imaging technology for medical fields, industrial nondestructive tests, public security, physical science, chemical analysis, life science, nanoscience biology and energy science.

1. Introduction

X-ray imaging has wide applications in many fields including medicine, biology, security, industry, food, materials and so on. Conventional hard X-ray imaging based on attenuation as contrast mechanism cannot obtain high-contrast absorption images for soft tissues and other low atomic number materials. For these materials, the phase factors are usually three orders of magnitude larger than their absorption factors [1]. Therefore, phase contrast imaging significantly improves the image contrast for these types of objects. Several types of X-ray phase contrast imaging techniques have been developed recently such as crystal interferometry, propagation-based imaging, analyzer-based imaging and grating-based imaging. The crystal interferometry and analyzer-based imaging rely on highly parallel and monochromatic X-ray beams due to the dependence on crystal optics. Although the propagation-based imaging such as the in-line phase-contrast method can overcome the stringent requirement on temporal coherence, it still requires the spatial coherence, which is currently only available from microfocus X-ray sources often associated with correspondingly low photon intensity or synchrotron radiation sources. The grating-based imaging can work on synchrotron radiation sources [2–6] and conventional X-ray sources [7–9]. It has many advantages over the others. For example, the grating-based differential phase-contrast imaging may be used to retrieve quantitative phase-contrast images with polychromatic X-ray sources of low brilliance [7,10,11], and has potential applications in ordinary laboratories with X-ray tube. The grating interferometer using specifically developed one dimension (1D) gratings [12,13] gives contrast for wave front deviations or scattering in the direction perpendicular to the grating lines. However, structures in the sample that are oriented perpendicular to the grating lines are not visible. In addition, retrieval of the wave front phase not only requires exact knowledge of the boundary values, but also induces substantial artifacts due to the lack of information on the “blind” direction. To overcome these limitations, grating-based imaging systems that use two dimension (2D) structures rather than 1D grating have been developed [14–16].

For the grating-based imaging methods, the gratings are the key optical elements, and the fabrication of an amplitude grating is accordingly very important. Recently, there are some means of fabricating the gratings such as X-ray lithography, vacuum deposition, and gold electrochemical plating. Because in the grating-based imaging system, the phase contrast increases with the decrease of the period of the grating, and the high resolution imaging also benefits from small grating periods, the grating with submicron periods are developed by using an array of multilayer stacks for the X-rays with energy below 25 keV. However, for most applications in clinical, industrial testing and security, the X-rays with higher energies are required. The main challenge for higher energies than 60 keV lies in the fabrication of gratings with a high-

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[*] Corresponding author at: College of Nuclear Science and Technology, Beijing Normal University, Beijing 100875, PR China.
E-mail address: stx@bnu.edu.cn (T. Sun).

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aspect-ratio pattern to provide sufficient image contrast. The reason for this is that transmission of the grating lines will cause a decrease in fringe visibility which deteriorates the image quality. Hence the pattern should accordingly be thick enough to block X-rays fully. Even when gold is adopted as a grating pattern material, the thickness should be several tens or several hundreds of microns [17]. Therefore, how to fabricate such gratings or their substitutions has attracted the concerns from the designer. For example, a structured scintillator grating has been used to replace the absorbing analyzer grating, and a multiline X-ray source is used as a replacement for the X-ray source and source grating [18]. An X-ray source with multiline metal targets embedded in a diamond substrate is used to replace the X-ray source and source grating [19,20]. 1D gratings with a combination of edge-on illumination and circularly aligned structures enable grating-based X-ray phase-contrast imaging at arbitrary design energies [17].

In this paper, the polycapillary optics was used to design high-aspect-ratio 2D gratings with grating periods from micron to several tens microns, which could be used at arbitrary required energies with an arbitrary designed aspect ratio. The performances of the polycapillary optics in the application in the X-ray Talbot interferometry were numerically studied.

2. Principles and numerical design of Talbot interferometer with polycapillary optics

The grating interferometer using the polycapillary optics is shown in Fig. 1. It consisted of a polycapillary parallel X-ray optics G_0 working as a source grating, a truncated cone-like polycapillary optics G_1 working as a phase shifting grating and a truncated cone-like polycapillary optics G_2 working as a analyzer grating. Such polycapillary optics consisted of many individual monocapillaries. The divergent X-ray beam from a conventional X-ray source with large source spot was collected by the source grating G_0 and collimated into a quasi-parallel beam. In this quasi-parallel beam, the X-rays from individual monocapillaries composing the source grating G_0 create a series of individual coherent, but mutually incoherent sources. As the polycapillary parallel X-ray optics G_0 can contain a large number of individual monocapillaries, each forming a sufficiently coherent virtual point source, conventional polychromatic X-ray sources with sizes of more than a square millimeter can be used.

Currently polycapillary X-ray optics are manufactured by the following method. A lot of single hollow glass tubes are combined together, and they are heated to its softening point and drawn through the drawing machine. During the process, those tubes extrude and restrict mutually, and finally deform into uniform orthohexagonal structure in the cross section, as shown in the Fig. 2. By controlling the speed of the drawing process, polycapillary can be obtained with different kinds of outlines, for example, the polycapillary with the cone-like shape that we discussed in this paper. Because of the manufacturing procedure, the stability of the hexagonal structure in polycapillary can meet the demands of the uniformity of the grating structure well to get a good spatial resolution.

Because such proposed polycapillary gratings as phase shifting grating and analyzer grating mentioned above were with a cone-like shape, the period of hexagonal structure will change between the entry and the outlet if the single hollow glass tubes that were combined together to be used to draw the polycapillary gratings were cylindrical. However, as the divergence angle of the cone-like shape is small and the number of period along the *Y*-axis and *X*-axis is large, the change of the period can be very small. For example, for a cone-like polycapillary with an aspect ratio $R=$ 40,000, the diameter of the entry is 1 cm and the period in the entry is 1 μm. The diameter of the outlet is 1.0024 cm, when the divergence angle is 0.6 mrad, and the length of the polycapillary grating is 2 cm. This means that the period of hexagonal structure will change from 1 μm at the entry to 1.0024 μm at the outlet.

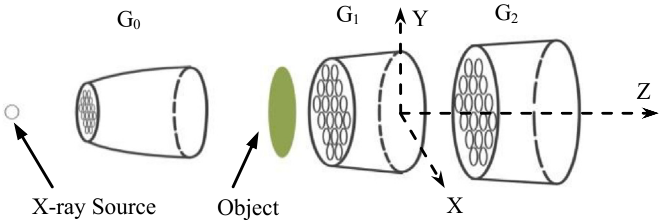

Fig. 1. Grating interferometer using the polycapillary optics.

The aspect ratio, *R*, is given by $R=2H/d$, where *d* is the grating period and *H* is the structure height shown in Fig. 2. The truncated cone-like polycapillary optics G_1 and G_2 have the same divergence as that of the quasi-parallel beam, namely, the truncated cone-like polycapillary optics G_1 and G_2 had the same profile as that of the quasi-parallel beam from the polycapillary parallel X-ray optics G_0. Therefore, such quasi-parallel beam can transform straightly through the grating structure. Moreover, the divergence of quasi-parallel beam is so small that it can be assumed as a plane wave, which can be approximatively predicted by the Fourier transform formulation.

Fig. 2 presents a cross section of the polycapillary phase shifting grating G_1. It shows a hexagonal lattice pattern with the period *d*. The periodicity of the complex transmission function of such a two-dimensional grating can be given as $T(\mathrm{r}) = T(\mathrm{r} + n\mathrm{a} + m\mathrm{b})$, where a and b are primitive vectors, and *n* and *m* are integer, respectively. $T(\mathrm{r})$ can be expressed with a Fourier-series expansion:

$$T(\mathrm{r}) = \sum\nolimits_{h,k} t_{h,k} \exp\ (\mathrm{i}\mathrm{g}\cdot\mathrm{r}), \tag{1}$$

where g is the reciprocal vector defined by $\mathrm{g} = h\mathrm{a}^* + k\mathrm{b}^*$, here a^* and b^* are the reciprocal primitive vectors, and *h* and *k* are integer, respectively. The Fourier coefficients *h*, *k* correspond to the structure factor that describes the magnitude of (hk) diffraction by the grating. Here, r denotes the position in the *X*–*O*–*Y* plane.

Under paraxial approximation, the wavefield at *z* from the grating can be given as

$$E(\mathbf{r}, z) = \sum_{h,k} t_{h,k} \exp\ \left(- \mathrm{i}\frac{\pi z(\Delta\theta_{hk})^2}{\lambda}\right) \exp\ (\mathrm{i}\mathbf{g}\cdot\mathbf{r}), \tag{2}$$

Where λ is the wave length and the $\Delta\theta_{hk}$ $(=\lambda|\mathrm{g}|/2\pi)$ is the beam deflection angle of the (hk) diffraction.

The light propagates in the *z* direction. As shown in Fig. 2, the angle between **a** and **b** is 120° and $|\mathrm{a}| = |\mathrm{b}| = d$, so we can get,

$$\Delta\theta_{hk} = \frac{2}{\sqrt{3}}\frac{\lambda}{d}\sqrt{h^2 + k^2 - hk}, \tag{3}$$

From Eqs. (2) and (3), when $E(\mathrm{r}, z)=T(\mathrm{r})$, we get the self-imaging positions,

$$z = Z_{\mathrm{T}} = \frac{3n}{2}\frac{d^2}{\lambda}, \tag{4}$$

where *n* is a positive integer.

By placing the polycapillary analyzer grating G_2 at Z_{T}, we assume that there is neither rotated angle in *Z* axes nor displacement in *X*,*Y* axes between the polycapillary phase shifting grating G_1 and the polycapillary analyzer grating G_2, then a moiré pattern $I(\mathrm{r})$ given by