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A dual detector approach for X-ray differential phase contrast imaging

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HIGHLIGHTS

- Dual detector approach for single-shot X-ray differential phase contrast imaging.
- Quantitative retrieval of the object's phase information by a single exposure.
- Advantageous in fast imaging speed and reduced radiation dose.

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ABSTRACT

Phase sensitive X-ray imaging methods can provide substantially improved contrast over conventional absorption-based techniques, and therefore new and inaccessible information. Here we propose a dual detector approach for X-ray differential phase contrast imaging, which allows a quantitative retrieval of the object's phase information by a single exposure. The analysis performed in our research shows that compared with the phase-stepping method, the dual detector approach is advantageous in fast imaging speed, reduced radiation dose and alignment errors, and avoiding any problems resulting from motion artifacts and X-ray exposure reproducibility. The approach has a direct extension to single exposure two-dimensional differential phase contrast imaging, as well as the possibility to perform three-dimensional reconstruction of the refractive index and its gradient field. We believe that this approach can find its potential in clinical applications, where imaging speed and radiation dose are critical issues.

1. Introduction

X-ray phase contrast imaging has attracting increasing attention over the last two decades, due to its capability to image weakly absorbing materials with increased contrast. Several phase-sensitive methods have been investigated to measure the phase shift of X-rays. They can be classified into crystal interferometry (Bonse and Hart, 1965; Momose et al., 1996), propagation-based imaging (Snigirev et al., 1995; Wilkins et al., 1996; Nugent et al., 1996), analyzer-based imaging (Davis et al., 1995; Chapman et al., 1997; Wernick et al., 2003), grating interferometry (David et al., 2002; Momose et al., 2003; Weitkamp et al., 2005; Pfeiffer et al., 2006, 2008; Zhu et al., 2010), and grating non-interferometric methods (Olivo and Speller, 2007; Munro et al., 2012). Particularly, X-ray differential phase contrast (DPC) imaging with grating interferometry is one of the most promising techniques. With respect to other techniques, it can offer high sensitivity and a large field of view. Most importantly, it is fully compatible with conventional tube sources. Its potential applications range from biomedical research, to material sciences, and to homeland security (Pfeiffer et al., 2007; Herzen et al., 2011; Stampanoni et al., 2011; Stutman et al., 2011).

To separate the phase information from other contributions, several methods have been introduced. They differ in the experimental procedure, the number of exposures, and the spatial resolution of the retrieved images. The commonly used phase-stepping method requires scanning one of the gratings while taking at least three exposures (Weitkamp et al., 2005). Thus, it is disadvantageous in terms of imaging speed and radiation dose. By contrast, the Fourier transform method requires only one single exposure, and is fast and dose efficient (Momose et al., 2011). However, the spatial resolution of the retrieved images, on the order of several hundred microns, is much worse than that of the detector. In this work, we propose a dual detector approach for X-ray differential phase contrast imaging, which extracts quantitatively the phase information of the object by a single exposure. Therefore, it overcomes the limitations of both low imaging speed and multiple exposures with respect to the phase-stepping approach, and maintains the resolution of the detector in the retrieved images compared to the Fourier transform method.

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2. Dual detector approach for X-ray differential phase contrast imaging

X-ray differential phase contrast imaging is based on the fractional Talbot effect of a grating. When a grating is illuminated with partially coherent X-rays, clear periodic intensity patterns, i.e., self-images, with periods corresponding to the pitch of the grating appear at specific distances from the grating (Guigay, 1971). As shown in Fig.1, for a π-shifting phase grating, its self-images are observed at the positions given by $d_m = mp^2/8\lambda$ (Suleski, 1997), where m is an odd integer, p is the grating pitch, and λ is the X-ray wavelength. Given the complex transmission function $T(x,y)$ of the grating with a Fourier expansion series

$$T(x,y) = \sum_n \alpha_n \exp\left(2\pi i \frac{nx}{p}\right) \tag{1}$$

Assuming unit-amplitude monochromatic plane-wave illumination, the wave field behind the grating is

$$E(x,y,z) = \sum_n \alpha_n \exp\left(-i\pi \frac{n^2\lambda z}{p^2}\right) \exp\left(2\pi i \frac{nx}{p}\right) \tag{2}$$

under a paraxial approximation. And the intensity of the wave field is given by

$$I_s(x,y,z) = |E(x,y,z)|^2 = \sum_n a_n(z) \exp\left(2\pi i \frac{nx}{p/2}\right) \tag{3}$$

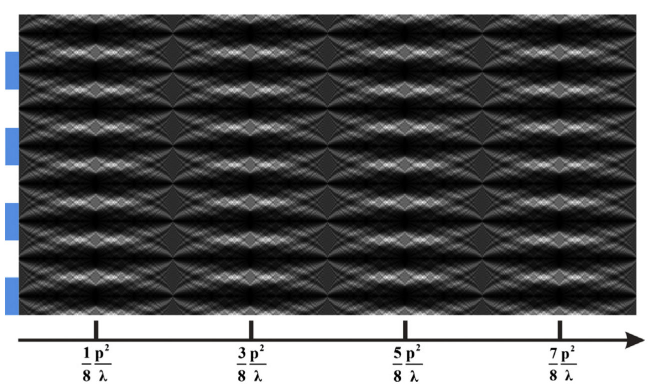

Fig. 1. Illustration of the fractional Talbot effect under plane-wave illumination. For a π-shifting phase grating, self-images are generated at $d = p^2/8\lambda$, $3p^2/8\lambda$, and so on. As seen, the self-image period p_2 is half of that of the phase grating.

where

$$a_n(z) = \sum_{n'} \alpha_{n+2n'} \alpha_{n'}{}^* \exp\left[-\frac{i\pi\lambda z}{p^2}(n+2n')^2\right] \exp\left(i\pi \frac{n'^2\lambda z}{p^2}\right) \tag{4}$$

Consider a case in which the X-ray wavefront is deformed due to the phase shift caused by an object placed in front of the grating. Consequently, the self-image is also deformed and its intensity becomes

$$I'_s(x,y,z) = \sum_n a'_n(x,y,z) \exp\left\{2\pi i \frac{n}{p}[x - d\theta(x,y)]\right\} \tag{5}$$

where a_n has been replaced by a'_n, which takes into consideration X-ray attenuation by the object, and

$$\theta(x,y) = \frac{\lambda}{2\pi} \frac{\partial \Phi(x,y)}{\partial x} \tag{6}$$

is the deflection angle induced by the object phase shift $\Phi(x,y)$ in the x direction (Born and Wolf, 1997). In X-ray DPC imaging, the recorded intensity for each detector pixel is the convolution of the self-image intensity with the transmission function of the phase-sensitive detector. Given the transmission function $t(x,y)$ of the detector with a Fourier expansion series

$$t(x,y) = \sum_n b_n \exp\left(2\pi i \frac{nx}{p_2}\right) \tag{7}$$

with $p_2 = p/2$, the recorded intensity is given by

$$I(x,y,z) = \sum_n a'_n(x,y,z) b_n \exp\left\{2\pi i \frac{n}{p_2}[x_g - d\theta(x,y)]\right\} \tag{8}$$

where x_g is the relative shift of the detector with respect to the self-image.

The proposed dual detector configuration is based on the manipulation of the relative shift between the two detectors located at different distances. As shown in Fig. 2, two phase-sensitive detectors with a transverse shift of $p_2/2$ are fixed on a optical rail. One is located at the 1st fractional Talbot distance, while the other at the 3rd fractional Talbot distance. Adopting the concept of Shifting Curve (Zhu et al., 2010), for detector-1 at the 1st fractional Talbot distance, the recorded intensity can be expressed as

$$I_1(x,y,d_1) = \frac{I_0}{M_1^2} \exp\left[-\int \mu(x,y,z)dz\right] S[x_g + d_1\theta(x,y)] \tag{9}$$

where I_0 is the intensity at the position of the grating G1 without object, $M_1 = (L + d_1)/L$ is the geometrical magnification, $\mu(x,y,z)$ is

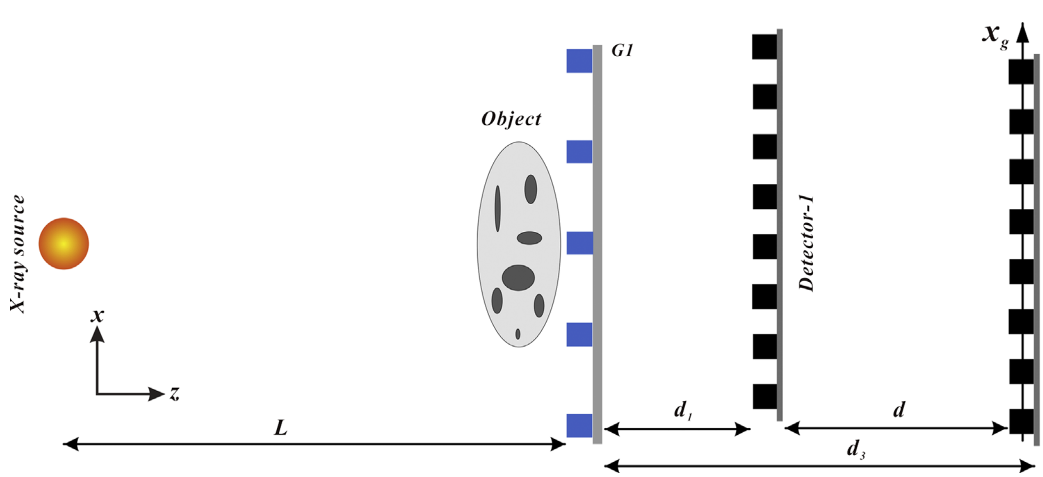

Fig. 2. Schematic configuration of the dual detector approach for X-ray differential phase contrast imaging. Two phase-sensitive detectors are located at the 1st and 3rd fractional Talbot distances, respectively, with a transverse shift of $p_2/2$ between them.