Radiation Physics and Chemistry ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Radiation Physics and Chemistry

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

Phase retrieval with the reverse projection method in the presence of object's scattering

Zhili Wang [a,*], Kun Gao [b], Dajiang Wang [b]

[a] School of Electronic Science & Applied Physics, Hefei University of Technology, Hefei 230009, China
[b] National Synchrotron Radiation Laboratory, University of Science and Technology of China, Hefei 230026, China

HIGHLIGHTS

- Accurate phase retrieval by the reverse projection method without object's scattering.
- Retrieved refraction signal contaminated by the object's scattering.
- Refraction signal underestimated by the reverse projection method.
- Guide the use of the reverse projection method for practical applications.

ARTICLE INFO

Article history:
Received 30 October 2015
Accepted 30 December 2015

Keywords:
X-ray imaging
Grating interferometry
Reverse projection
Phase retrieval

ABSTRACT

X-ray grating interferometry can provide substantially increased contrast over traditional attenuation-based techniques in biomedical applications, and therefore novel and complementary information. Recently, special attention has been paid to quantitative phase retrieval in X-ray grating interferometry, which is mandatory to perform phase tomography, to achieve material identification, etc. An innovative approach, dubbed "Reverse Projection" (RP), has been developed for quantitative phase retrieval. The RP method abandons grating scanning completely, and is thus advantageous in terms of higher efficiency and reduced radiation damage. Therefore, it is expected that this novel method would find its potential in preclinical and clinical implementations. Strictly speaking, the reverse projection method is applicable for objects exhibiting only absorption and refraction. In this contribution, we discuss the phase retrieval with the reverse projection method for general objects with absorption, refraction and scattering simultaneously. Especially, we investigate the influence of the object's scattering on the retrieved refraction signal. Both theoretical analysis and numerical experiments are performed. The results show that the retrieved refraction signal is the product of object's refraction and scattering signals for small values. In the case of a strong scattering, the reverse projection method cannot provide reliable phase retrieval. Those presented results will guide the use of the reverse projection method for future practical applications, and help to explain some possible artifacts in the retrieved images and/or reconstructed slices.

1. Introduction

X-ray phase contrast imaging has attracting increasing attention over the last two decades, owing to its capability to image weakly absorbing features with an increased contrast. Several phase-sensitive techniques have been developed to measure the phase shift of X-rays (Bonse and Hart, 1965; Momose et al., 1996; Wilkins et al., 1996; Nugent et al., 1996; Davis et al., 1995; Chapman et al., 1997; Momose et al., 2003; Weitkamp et al., 2005). Particularly, X-ray grating interferometry is one of the most promising techniques, due to its high sensitivity and a large field of view. Most importantly, it is fully compatible with conventional tube sources (Pfeiffer et al., 2006, 2008). Therefore, its potential applications range from biomedical research, to material sciences, and to homeland security (Stampanoni et al., 2011; Herzen et al., 2011; Wang et al., 2014).

In X-ray grating interferometry, the measured projection images contain a mixture of absorption, refraction (i.e., differential phase) and scattering signals. Several approaches have been proposed for quantitative phase retrieval, which is mandatory to perform phase tomography, to discriminate different types of tissues, and so on. The commonly used phase stepping technique requires grating scanning and acquisition of multiple images (Weitkamp et al., 2005). Thus, it is disadvantageous in terms of imaging speed and potential radiation damage. By contrast, the

* Corresponding author. Tel.: +86 551 63602017; fax: +86 551 65141078.
E-mail address: dywangzl@hfut.edu.cn (Z. Wang).

http://dx.doi.org/10.1016/j.radphyschem.2015.12.026
0969-806X/

Fourier transform method requires only one single exposure, and is therefore fast and dose efficient (Momose et al., 2011). However, the spatial resolution of the retrieved images is much worse than that of the detector.

Recently, an alternative approach, named "Reverse Projection" (RP), has been proposed for quantitative phase retrieval. This method abandons grating scanning completely, and maintains the spatial resolution of the detector in the retrieved images. Strictly speaking, the RP method is applicable for objects exhibiting only absorption and refraction. However, the object's scattering can also be quite useful for specific applications, such as breast cancer detection (Wang et al., 2014). In this work, we discuss the phase retrieval with the RP method for objects exhibiting absorption, refraction and scattering simultaneously. Especially, we investigate the influence of the object's scattering on the retrieved refraction signal through theoretical analysis and numerical experiments. The obtained results can be used as guidelines to perform phase retrieval with the reverse projection method, and help to explain some artifacts in the retrieved images and/or reconstructed slices.

2. Phase retrieval with the reverse-projection method in X-ray grating interferometry

X-ray grating interferometry when implemented with synchrotron radiation sources is schematically presented in Fig. 1(a). Through the fractional Talbot effect, the self-image of the phase grating G1 is formed on the analyzer absorption grating G2, with the inter-grating distance d set to one of the fractional Talbot distances of G1. When an object is placed in the beam, the self-image is locally deformed due to the X-ray attenuation, refraction and scattering. The deformation is then analyzed by G2 and transformed into intensity variations measured by the detector. When one of the gratings is scanned along the transverse direction, the intensity signal in each pixel in the detector plane oscillates as a function of the relative position of G2 against G1's self-image of x_g. For an object exhibiting absorption, refraction and scattering, the measured intensity in each detector pixel is given by (Bech et al., 2010).

$$I(x, y; x_g) = I_0 T(x, y)\left\{1 + V_0 S(x, y)\cos\left[kx_g + kd\theta(x, y)\right]\right\} \tag{1}$$

where I_0 is the intensity incident on the object, $T(x, y)= \exp[-\int\mu(x, y, z)dz]$ represents the object's transmission with $\mu(x, y, z)$ being the linear attenuation coefficient, V_0 is the reference visibility without the object, $S(x, y) = \exp[-2\pi^2\sigma^2(x, y)d^2/p^2]$ represents the object's scattering with σ^2 being the second moment of the Gaussian distribution, p is the grating period, $k = 2\pi/p$, and the refraction signal $\theta(x, y)$ is related to the first-order spatial derivative of the object's phase shift $\Phi(x, y)$,

$$\theta(x, y) = \frac{\lambda}{2\pi}\frac{\partial\Phi(x, y)}{\partial x} = -\int\frac{\partial\delta(x, y, z)}{\partial x}dz \tag{2}$$

where $\delta(x, y, z)$ is the real part of the object's refractive index.

In the following, we will discuss the phase retrieval with the reverse projection method. Detailed explanations of the principle of the reverse-projection method have been presented by Wang et al. (2013). Its experimental procedure has also been described by Zhu et al. (2010). As required by the reverse projection method, during data acquisition, the relative position x_g is fixed at either $x_g^L = -p/4$ (the so-called left half-slope) or $x_g^R = p/4$ (the so-called right half-slope), as indicated in Fig. 1(b). The idea behind this setting is that the first-order derivative of the intensity curve, i.e., the sensitivity to the refraction signal, is maximized at those working points. Therefore, for small values of θ satisfying $|\theta| \le p/4d$, one can apply the first-order linear approximation of Eq. (1) around $x_g^R = p/4$, and yields

$$\begin{aligned} I(x, y; p/4) &\cong I_0 T(x, y)\left[1 + V_0 S(x, y)\cos\left(\frac{kp}{4}\right) + V_0 S(x, y)\sin\left(\frac{kp}{4}\right)kd\theta(x, y)\right] \\ &\cong I_0 T(x, y)\left[1 - V_0 S(x, y)kd\theta(x, y)\right] \end{aligned} \tag{3}$$

Secondly, for phase retrieval under a projective angle Θ, two projection images are measured at the projective angles Θ and $\Theta + \pi$, and by use of Eq. (3), the corresponding intensities are respectively given by,

$$I_\Theta(x, y; p/4) = I_0 T_\Theta(x, y)\left[1 - V_0 S_\Theta(x, y)kd\theta_\Theta(x, y)\right] \tag{4}$$

$$\begin{aligned} &I_{\Theta+\pi}(-x, y; p/4) \\ &\quad = I_0 T_{\Theta+\pi}(-x, y)\left[1 - V_0 S_{\Theta+\pi}(-x, y)kd\theta_{\Theta+\pi}(-x, y)\right] \end{aligned} \tag{5}$$

Eq. (5) can be further simplified by use of the following relation,

$$T_{\Theta+\pi}(-x, y) = T_\Theta(x, y) \quad S_{\Theta+\pi}(-x, y) = S_\Theta(x, y) \quad \theta_{\Theta+\pi}(-x, y) = -\theta_\Theta(x, y) \tag{6}$$

which then results in

$$I_{\Theta+\pi}(-x, y; p/4) = I_0 T_\Theta(x, y)\left[1 + V_0 S_\Theta(x, y)kd\theta_\Theta(x, y)\right] \tag{7}$$

With Eqs. (4)–(7) as input, the refraction (i.e., differential phase) signal can be retrieved by use of the reverse projection method,

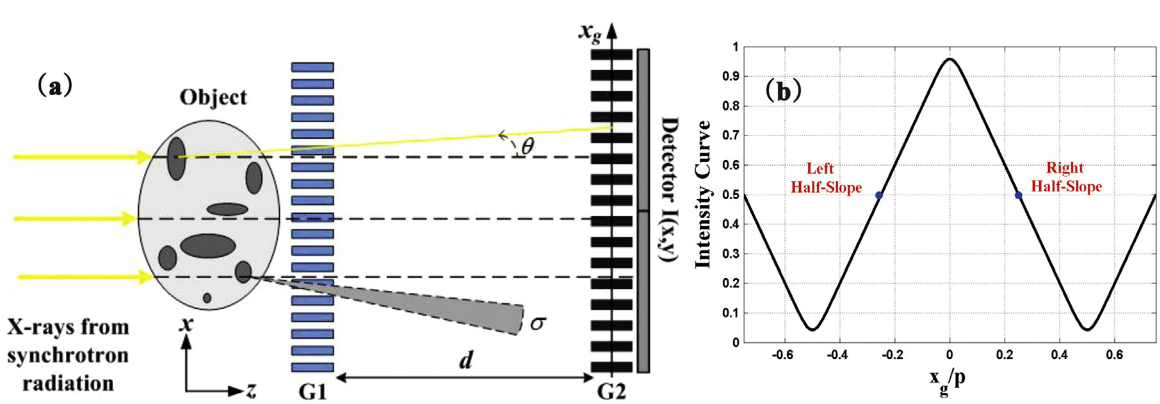

Fig. 1. (a) Schematic of X-ray grating interferometry using synchrotron radiation sources. When passing the object, the X-rays can be attenuated, refracted (angle θ), or scattered (angular spread σ) as illustrated. This induces local deformations in the self-image patterns. (b) Plot of the intensity curve I (x, y) as a function of the grating position x_g in units of the grating period.

Please cite this article as: Wang, Z., et al., Phase retrieval with the reverse projection method in the presence of object's scattering. Radiat. Phys. Chem. (2016), http://dx.doi.org/10.1016/j.radphyschem.2015.12.026