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Laboratory-based quantitative hard x-ray phase microscopy in one dimension using waveguides

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ABSTRACT

We report on the quantitative hard x-ray phase microscopy obtained with a laboratory source equipped with an x-ray planar waveguide. The waveguide, acting as a small secondary source with increased coherence, allows for phase contrast microscopy to be measured from a phase-only one-dimensional object. We analyzed different strategies and their performances for the case studied of low absorbing one-dimensional sample. It was found that the phase-only approximation for the sample enables the best performance in phase retrieval. Results obtained from experimental data are supported by phase retrieval performed on simulated data allowing an estimation of the performance of the algorithms. The ability to perform quantitative phase contrast microscopy with waveguides is an important advance for this novel x-ray phase contrast method, well suited to compact laboratory setups.

1. Introduction

Phase contrast (PC) x-ray imaging is a useful analytic tool which provides unique information on the internal structure, interfaces and thickness of samples that have very low absorption [1,2]. Unlike absorption imaging, phase contrast aims at measuring phase changes that occur due to differences in a samples thickness or optical density. For biological samples, the variation from unity of the real part of the refractive index is much greater than the variation in absorbance (related to the imaginary part of the complex refractive index) when hard x-rays are used. Thus as the real part of the refractive index alters only phase, very high contrast can be attained by developing phase sensitive imaging techniques.

While there are numerous different methods for undertaking PC imaging [1,2], propagation-based PC imaging [3] is the easiest to implement experimentally. It requires no optics and the recorded image features edge enhancement due to PC effects arising when the wave front interferes upon crossing an interface between two materials. The edge enhancement appears when the detector is placed further downstream from the sample to allow enough distance for cumulative interference effects to be easily detectable. The main requirement of propagation-based PC imaging is a sufficient degree of coherence of the illuminating field [4,5] which can be obtained with a synchrotron source or with a microfocus x-ray source. Depending on the attainable spatial resolution, the latter method, based on the geometrical magnification of the sample image onto the detector plane, is termed projection microscopy. Reducing the dimension of the x-ray source (or its divergence) is the key to obtain a sufficient degree of coherence [6]. Recently, an experimental setup, able to produce a sub-micrometer x-ray beam for projection microscopy with laboratory sources, was demonstrated using x-ray waveguides in 1D [7] and 2D [8]. The principle of operation of an x-ray waveguide (WG) is total internal reflection occurring at the interface between a layer and a surrounding medium with lower refractive index. For x-ray operations, being the refractive index of all material less than unity, a WG can be obtained by an empty channel surrounded by reflecting surfaces [9,10]. The guiding channel can be made of micron or sub-micron width and therefore, when a WG is coupled to a standard x-ray source, it filters the incoming radiation, effectively acting as a small secondary source. Moreover the multiple interference occurring when x-rays propagates along the channel (resonator), contribute to improve the degree of coherence of the incoming radiation by reducing the number of modes sustained by the resonator [11,12].

High resolution projection microscopy in 1D [7] and 2D [8] has been demonstrated coupling x-ray WGs to laboratory tubes. However, quantitative phase retrieval using this configuration has not yet been achieved. This is specifically the topic of this paper.

Whilst propagation-based PC x-ray imaging provides detailed information on the sample, it does not directly reveal the phase shift induced by it on the incoming wave front which can be the quantity of interest. Phase retrieval techniques must be used to

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extract the phase information from the data [13,14]. A variety of approaches can be used, the choice of the best algorithm depending on the sample characteristics and the imaging geometry [15–18]. In this paper we investigate different strategies for phase retrieval that can be used to retrieve the projected thickness of a homogeneous mono-material object. The performances of the different approaches are compared for the configuration under study, i.e. the one-dimensional projection microscopy using a planar WG as secondary source. We find that approximating the sample by a phase-only object enables better phase retrieval results for experimental data. This finding is supported by subsequently performing phase retrieval on simulated data with different values of the refractive index. This information will be valuable to future PC imaging experiments using WGs or other microfocus x-ray sources in which the accurate phase retrieval may be the desired outcome.

The paper is organized as follows: in Section 2 we shall introduce the theoretical background, reviewing the algorithms used for the phase retrieval. In Section 3 the experimental setup and the PC data are presented. Section 4 is devoted to describing the phase retrieval of the experimental data, followed by the phase retrieval of simulated data to support and critically analyze the results. Conclusions are drawn in Section 5.

2. Theoretical background

In many imaging problems, x-ray free-space propagation is conveniently described with the Transport of Intensity Equation (TIE) [19], obtained from the Helmholtz equation using the paraxial approximation. In this paper we are dealing with a two-dimensional (2D) propagation problem, as described in the schematic drawing of Fig. 1. The propagation distance is denoted by z and the transverse direction (the direction in which the PC is measured) is denoted by x. The 2D TIE has the form:

$$-k\partial_z I_0(x) = \partial_x[I_0(x)\partial_x\phi_0(x)]. \tag{1}$$

In Eq. (1) $\partial_x = \partial/\partial x$ and similarly for ∂_z, $k = 2\pi/\lambda$ is the wave number and λ is the wavelength. $I_0(x) = |U(x, z=0)|^2$ is the intensity measured along the transverse direction x and $\phi_0(x)$ the corresponding phase associated with the unpropagated complex field $U(x, z=0)$. By approximating

$$\partial_z I_0(x) \approx \frac{I_R(x) - I_0(x)}{R}, \tag{2}$$

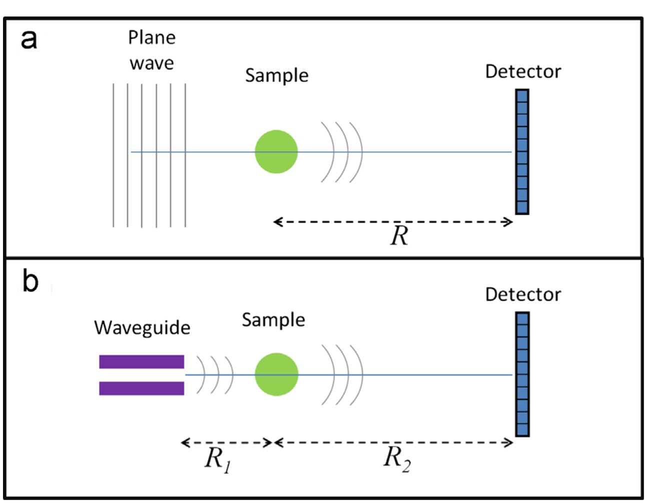

Fig. 1. Schematic drawings of the 1D microscopy experiment. (a) Plan wave illumination. (b) Cylindrical wave illumination with a WG used as a secondary x-ray source.

R being the sample-detector distance, Eq. (1) assumes the convenient form:

$$I_R(x) \approx I_0(x) - \frac{R}{k}\partial_x[I_0(x)\partial_x\phi_0(x)]. \tag{3}$$

An important solution of Eq. (3) has been obtained by Paganin et al. [20] in the approximations of homogeneous, mono-material thin sample. In this case the unpropagated intensity is expressed by a simple Beer–Lambert law of absorption: $I_0(x) = I_{in}(x)\exp(-\mu T(x))$, where $I_{in}(x)$ is the incidence intensity (before the sample) and $\mu = 4\pi\beta/\lambda$ is the linear absorption coefficient, connected to the imaginary part of the complex refractive index $n = 1 - \delta + i\beta$. $T(x)$ is the sample complex transmission function. Such an assumption leads to the following expression for the transmission function (see [20] for the derivation of this result):

$$T(x) = -\frac{1}{\mu}\ln\left(\mathcal{F}^{-1}\left[\mu\frac{\mathcal{F}[I_R(x)/I_{in}(x)]}{R\delta k_x^2 + \mu}\right]\right). \tag{4}$$

In Eq. (4), the symbol $\mathcal{F}$ denotes the Fourier transform, $\mathcal{F}^{-1}$ its inverse and k_x the Fourier coordinate corresponding to x.

A further simplification can be made when the sample can be approximated as a homogeneous phase-only object with $\beta = \mu = 0$ and $I_0(x) = I_{in}(x)$. In this case a simpler version of the TIE equation is found [21]:

$$\partial_x^2\phi_0(x) \approx \frac{R}{k}\left(1 - \frac{I_R(x)}{I_{in}(x)}\right). \tag{5}$$

For a homogeneous phase-only sample $\phi_0(x) = -k\delta T(x)$, therefore the transmission function of the sample can be derived at once from the measured intensity via

$$T(x) = -\mathcal{F}^{-1}\left[\frac{\mathcal{F}[I_R(x)/I_{in}(x) - 1]}{R\delta k_x^2}\right]. \tag{6}$$

It is worth noting that this procedure is sometimes referred to as “Bronnikov algorithm”, after Bronnikov [22], who combined the use of Eq. (6) in a single step with tomographic back-projection.

In many practical uses of Eq. (6), a phenomenological regularization parameter α is introduced at the denominator, to avoid the singularity at $k_x = 0$, as proposed by Groso et al. [23]:

$$T(x) = -\mathcal{F}^{-1}\left[\frac{\mathcal{F}[I_R(x)/I_{in}(x) - 1]}{R\delta k_x^2 + \alpha}\right]. \tag{7}$$

Such a regularization parameter is not needed in the retrieval procedure in Eq. (4) as the linear absorption coefficient itself serves this function.

An alternative method to the introduction of a regularization parameter is to use Eq. (6) and subsequently impose the value of the function within the square bracket in $k_x = 0$ to be equal to the value of the Fourier transform of the function obtained by direct integration of the differential phase image for $k_x = 0$ (see [24] where this procedure was applied in the case of the first derivative of the phase).

The latter approach is found to produce the best result in our case of 1D phase retrieval. In fact while computationally less demanding, the 1D case is actually more delicate to deal with numerically, as the numerical problem is far less constrained than a conventional 2D phase retrieval.

Finally, we remark that the derivations outlined above are valid for parallel beam illumination, i.e., a point source located infinitely far downstream of the sample and a distance R between sample and detector (Fig. 1 (a)). To account for projection microscopy – cylindrical wave illumination in the 1D problem – with finite source-sample distance R_1 and sample-detector distance R_2 (see Fig. 1(b)), one can make use of the Fresnel scaling theorem [14,20] which prescribes for the following substitutions to be made in Eqs.