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Single grating method for low dose 1-D and 2-D phase contrast X-ray imaging

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ABSTRACT: X-ray phase contrast imaging (XPCI) using a single absorption grating and a hybrid semiconductor pixel detector is a newly introduced approach with great potential for application in medicine, biology and material research. In comparison with a conventional grating interferometer technique, which requires a multiple-exposure (phase-stepping) procedure, our method is greatly simplified, because both phase gradient and absorption images are obtained from just one exposure. Consequently, the approach can significantly reduce the time-consuming scanning and also possibly the unnecessary dose. Examples of application of the single-grating approach as an imaging tool for investigations in biology are presented. Particularly, we present the extension of our 1-D single grating method to a two-direction sensitive technique. The novel 2-D sensitive XPCI method is based on precise sub-pixel position determination of the X-ray pattern projected by the two-dimensional transmission grating directly from the pattern image. In a single exposure, phase gradient images in two perpendicular directions together with the conventional attenuation image are produced. Results of the proof-of-concept experiment are presented.

KEYWORDS: Inspection with x-rays; X-ray radiography and digital radiography (DR); Image reconstruction in medical imaging; X-ray detectors

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1 Introduction

X-ray absorption imaging is a standard tool in medical diagnostics and is increasingly used in other research areas such as biology and materials science. Despite the progress in detector technology, for certain types of samples, such as biological tissue or polymers, the use of conventional X-ray radiography is limited because, for a reasonable dose, these objects show poor absorption contrast. It has been demonstrated, that phase sensitive X-ray imaging, which uses phase shift rather than beam attenuation as a contrast imaging signal, is a powerful imaging technique providing high sensitivity even for weakly absorbing objects [1]–[10]. Furthermore, the measurement of the phase shifts of the X-rays waveform traveling through the inspected object enables one to reach substantially higher contrast with significantly lower dose [5].

1.1 Conventional X-ray phase contrast imaging (XPCI)

During the last four decades XPCI has been intensively studied and several approaches for X-ray phase retrieval enabling to measure the phase variations induced by an investigated object have been developed. They can be classified into free-space propagation techniques [2], interferometric methods [4], setups using an analyzer crystal [1], or grating interferometers [11]. The crystal interferometer uses Bragg reflection as a beam splitter, and the recorded signal measures the phase shift (Φ) directly. With the analyzer-based imaging method, the Bragg crystal enables to measure the first spatial derivative of the phase (∇Φ). For propagation-based phase imaging, where the measured quantity corresponds to the second derivative of the phase (ΔΦ), the in-line method is often used, where the effects of phase contrast become evident, as the sample-detector distance is increased.
However, because of the use of crystal optics, there are very stringent requirements on the X-ray source parameters (very high intensity, high spatial and temporal coherence) and the experimental setup as a whole (large source-to-detector distance, extreme requirements on the setup stability) restricting the methods mainly to synchrotron radiation facilities.

### 1.1.1 Grating interferometer approach

At present, the largest potential by the XPCI methods, enabling high-quality imaging in a table-top setup, is the grating based approach [11]–[13]. This method provides all the benefits of contrast-enhanced phase-sensitive imaging, but is also fully compatible with conventional absorption radiography. During the last years it has been demonstrated that phase contrast imaging with a grating interferometer can be efficiently performed with a conventional, low-brilliance X-ray source [13]. Furthermore, the ability of the grating interferometer to measure concurrently images based on the local scattering power of the sample (dark field images) was demonstrated [14].

For the phase-gradient retrieval, current grating-based methods need a phase or an absorption grating to produce the intensity distribution as well as a separate absorption grating to analyze the intensity distribution by a phase-stepping method [12] (see figure 1a). During phase-stepping, the grating is scanned transversely to the incident beam while acquiring multiple projections. The sample is supposed to be static, and the resulting poor time resolution is one of the major drawbacks of this method. Moreover, phase stepping necessarily implies multiple exposures and, in comparison with current conventional absorption imaging techniques, the dose upon phase-stepping tends to be too high. This limitation prevents the widespread use of the technique, e.g., into clinical practice.

Thus, the development of an approach enabling, in a single exposure to retrieve concurrently the phase, absorption and possibly local scattering power information is desirable. This feature opens possibilities for widespread applications (e.g., medical and imaging of dynamical processes, direct extension to 2-D phase contrast sensitivity in a single exposure, low dose phase-contrast tomography). Up to now, most of these issues remain unsolved or solved unsatisfactorily in relation to real-world applications.

### 1.1.2 Single absorption grating & high spatial resolution detector approach

The method utilizing high resolution X-ray detector together with a single absorbing grating is a single exposure approach enabling quantitative XPCI. The method was recently discussed by Z. Wang et. al [15] and the application of the approach for dynamical XPCI studies was demonstrated [16]. The approach has also its own two-direction sensitive variation, as demonstrated in ref. [17]. For the image retrieval, the intensity distribution downstream of the grating is recorded and analyzed directly from a single exposure data (i.e., there is no need of phase-stepping) using a spatial phase demodulation method. Simplicity and minimal requirements on the setup alignment are the main advantages of the approach. However, to retrieve the phase-gradient image, the pattern projected by the attenuation grating has to be sampled sufficiently by the X-ray detector used. This requirement naturally results in an unpleasant reduction of the natural spatial resolution of the detector appearing in the final XPCI image. A possible solution to these obstacles is the application of an extremely high granularity detector (pixel pitch \( \sim 1 \mu m \)). However, there is naturally a poor compromise between pixel pitch and the respective pixel signal-to-noise ratio, resulting again in dose limitations.
Figure 1. Current grating-based methods (a) require a phase or an absorption grating (1) to produce the intensity distribution and another absorption grating (2) to analyze the intensity distribution by the phase-stepping method. In the single-grating absorption XPCI technique (b) the detector grating (2) are removed and the phase gradient signal is calculated directly from the detector signal. The investigated object can be placed in front of or behind the grating. If the detector resolution is sufficiently high to sample each projected pattern strip, the phase gradient image can be retrieved using the Fourier based demodulation method. Another approach for single grating XPCI is the usage of a highly sensitive hybrid semiconductor detector such as Medipix type with sub-pixel resolution data capability [19].

1.1.3 Single absorption grating & hybrid semiconductor pixel detector approach

In our previous work [18], we have demonstrated that the phase gradient information can be obtained thanks to sub-pixel resolution, which can be directly obtained from the high-sensitivity counting pixel detector in a setup with micro-focus X-ray tube and simple coded aperture. Based on this sub-pixel resolution principle, we have introduced a new XPCI approach using the single absorption grating and hybrid semiconductor pixel detector [19] (see figure 1b). The approach enables achieving high quality phase gradient and absorption images (both images obtained from one exposure) without time-consuming phase stepping and with possible better dose utilization. The technique works with a fully polychromatic spectrum and gives ample variability in object magnification. Consequently, the approach can open the way to further widespread application of phase contrast imaging, e.g., into clinical practice.
1.2 Two-dimensional (2-D) XPCI

The advantages of the two-dimensional sensitivity have been discussed since the XPCI technique was pioneered. In the grating based XPCI, the quantity that serves as imaging information is not the wave-front phase profile $\Phi(x,y)$, but its first derivative along the axis perpendicular to the grating lines $\Phi_x = \partial \Phi(x,y)/\partial y$ (see figure 1). Thus this technique is called differential phase-contrast imaging (DPC).

Some quantitative analysis and signal processing can require retrieval of the wave front profile $\Phi(x,y)$. In principle, the full phase profile, which is equivalent to the integral of the index of refraction along to the beam path of the investigated object, can be done by a straightforward one-dimensional integration. In practice, the integration very often results, however, in phase images that suffer from unfavorable artifacts due to noise in the image (e.g., low number of detected photons) or unknown boundary conditions (the investigated object is larger than the field of view). The natural solution to these obstacles is a measurement of the phase gradient in two independent directions enabling, using special integration algorithms, reconstruction of the phase profile of excellent quality even in the case when the 1-D algorithm completely fails [20].

Together with the method allowing to measure 2-D DPC images under reasonable conditions (with exception of the approach discussed in ref. [17], for real-world measurement unacceptable multiple application of the 1-D approach is used) this clearly opens the way, e.g., for further dose reduction. In this contribution, we focus on the extension of our 1-D single grating method [19] to the 2-D sensitive approach. The novel 2-D sensitive XPCI method is based on precise sub-pixel position determination of the X-ray pattern projected by the two-dimensional transmission grating directly from the pattern image. In a single exposure, phase gradient images in two perpendicular directions together with the conventional attenuation image are measured.

2 Principles and methods

The phase of spatially coherent X-ray waves passing through the object is shifted according to the gradient of the effective index of refraction (the gradient is perpendicular to the beam path). Consequently, X-rays are deflected from their original direction of propagation which results in a projected pattern shift as indicated in figure 1. The local beam deviation $\alpha$ (or, equivalently, the pattern shift on the detector) is linearly proportional to the local gradient of the phase waveform $\Phi(y,z)$ and can be quantified as [21]

$$\alpha(y,x) = \frac{\lambda}{2\pi} \frac{\partial \Phi(x,y)}{\partial y} = \int_{-\infty}^{+\infty} \frac{\partial \delta(x,y,z)}{\partial y} dz$$

where $\lambda$ is the wavelength of the incident X-rays, $y$ is the direction of the phase gradient calculation (perpendicular to the beam propagation), and $\delta(x,y,z)$ is the decrement of the real part of the object’s refractive index. In the grating based XPCI, due to the shape of the gratings and, more importantly, due to the phase stepping procedure, the pattern shift is calculated only in one direction perpendicular to the grating lines. However, according to eq. (2.1), the phase gradient image is given as a map of displacement of the pattern projected by the grating in the cases with and without the object. Thus, when an appropriate 2-D attenuation grating is used, the pattern shift (equivalent
Figure 2. Illustration of the setup alignment for the 1-D single grating approach: (a) position of the projected X-ray pattern (pink stripes) on the detector in the case when the condition of eq. (2.2) is fulfilled \( n = 2 \) and in the situation when the grating strips are aligned parallel to the detector columns. Positions of the projected X-ray beams irradiating two adjacent pixels without (b) and with (c) the measured object. The alignment enables to measure the shift \( d \) and attenuation of the projected strips just using the respective intensities \( I_1, I_2, I_3, I_4 \) utilizing eq. (2.3) and eq. (2.4), respectively [19].

The phase wave-front gradient) can be measured concurrently in two directions perpendicular to each other and to the beam path. In principle, there is no need for multiple exposures (as well as in the case of the 1-D XPCI imaging).

2.1 1-D setup geometry

In our one-dimensional single grating XPCI approach, an absorption grating is imaged first without and then with the investigated object. The displacement calculations are performed using sub-pixel resolution in a setup aligned according to the condition

\[
T \cdot M = n \cdot s
\]

where \( T \) is the periodicity of the grating, \( M \) is the geometrical magnification of the grating, \( n = 2, 3, 4, \ldots \) and \( s \) is the detector pitch. Fulfillment of eq. (2.2) together with the alignment of the grating strips parallel to the detector columns ensure that every projected X-ray sub-beam formed at a certain gap of the grating irradiates the detector in the same position in relation to the pixel matrix (see figure 2). The pattern shift \( d \) representing the phase gradient information and the corresponding absorption image \( A \) can be then calculated simply from one-exposure data (intensity labeled as \( I_1, I_2, I_3, I_4 \), see figure 2) [19]:

\[
d = p_2 \cdot \left( \frac{I_1}{I_2} - \frac{I_3}{I_4} \right) \cdot \left( 1 + \frac{I_3}{I_4} \right)^{-1}
\]

\[
A = \frac{I_3 + I_4}{I_1 + I_2}.
\]
Figure 3. Setup for the 2-D single grating method. The phase of the spatially coherent X-ray waves passing through the object is shifted according to the gradient of the effective index of refraction. Consequently, X-rays are deflected from their original direction of propagation which results in a projected pattern shift. In the proposed method, the pattern shift in two perpendicular directions is calculated directly from the detector signals $I_1, I_2, I_3, I_4$ using sub-pixel resolution made possible by the use of highly sensitive hybrid pixel semiconductor detector of the Medipix type.

2.2 2-D setup geometry

A newly introduced two-dimensional XPCI method is the direct extension of the 1-D XPCI approach discussed above and, in more detail, in ref. [19]. This novel 2-D method works similarly with a single absorbing grating and a hybrid semiconductor pixel detector of the Medipix type [22]. The pattern downstream is directly recorded by the detector and, using sub-pixel resolution data handling, the phase gradient images in two perpendicular directions together with the conventional attenuation image are calculated.

Instead of a 1-D transmission grating (parallel strips), a two-dimensional transmission grating is used (see figure 3). In principle, the shape of the grating opening (projected pattern shape) can be chosen independently from the shape of the detector pixel; nevertheless, the usage of a square-shaped geometry is very desirable in relation to the pattern shift calculation. When the squared geometry of the openings is used (see figure 4) and when eq. (2.2) remains valid for both pixel matrix directions, the pattern shift calculation in both directions can be performed simply according to the same relation which is used in the 1-D approach.

Labeling the intensity in the respective neighboring four pixels $I_1, I_2, I_3$ and $I_4$ in the case without the object and $I_1', I_2', I_3'$ and $I_4'$ in the case with the object (see figure 4), then the horizontal shift $d_H$, vertical shift $d_V$ and attenuation image $A$ can be calculated as:

$$d_H = p_1 \left( \frac{I_1}{I_2} - \frac{I_2'}{I_1'} \right) \cdot \left( 1 + \frac{I_1}{I_2} \right)^{-1},$$

$$d_V = p_3 \left( \frac{I_3}{I_3'} - \frac{I_3'}{I_3} \right) \cdot \left( 1 + \frac{I_3}{I_3'} \right)^{-1},$$

$$A = \frac{I_1 + I_2 + I_3 + I_4}{I_1' + I_2' + I_3' + I_4'}. \quad (2.5)$$

$$A = \frac{I_1 + I_2 + I_3 + I_4}{I_1' + I_2' + I_3' + I_4'}. \quad (2.6)$$
Figure 4. Position of the original (dashed line) and refracted beam (in pink). The non-symmetrical initial beam alignment is more convenient for practical measurements. In this case the intensity signals $I'_1$, $I'_2$, $I'_3$, $I'_4$ (without the object) has to be measured.

Figure 5. Phase gradient images of a cylinder of Plexiglas of 2 mm diameter measured with the ideal grating design ($n = 2$ in eq. (2.2)). In a single exposure, the natural spatial resolution of the detector 256 x 256 is reduced by a factor of 2 in the direction of the phase contrast measurement. Image taken with a non-filtered tungsten spectrum at 50 keV. The cross sectional view profile (one row data without any filtering) taken at positions indicated by the red line shows perfect agreement with the theoretical prediction (differentiation of the circle function), which proves that the method generates clear quantitative information with possibility to use two different direction of the phase wave-front differentiation for its backward reconstruction.

3 Experimental

3.1 One-dimensional single grating XPCI

The single grating method not only generates a form of phase contrast, but also provides clear quantitative phase information, as demonstrated in figure 5. This feature is crucial in relation to final image quality, because (as discussed in section 1.2) using two different directions of the phase gradient measurement one can perform advanced image analysis, e.g., backward phase wave-front reconstruction.

The single grating method is fully compatible with conventional attenuation imaging. The method provides all the benefits (non-destructive technique with possibility for tomographic reconstruction, imaging of dynamical processes, etc.). Moreover, the phase gradient image is acquired from the same single exposure (see figure 6).
Figure 6. Example of application of the single grating object for non-destructive imaging in biology: (a) Absorption and (b) phase gradient image of the bone dry head of a hornet, (c) absorption and (d) phase gradient image of a mouse leg. All images were taken on a 35 keV tungsten spectrum.

3.2 Two-dimensional single grating XPCI

As verification of reliability of the proposed 2-D method we reproduced the image of a well defined geometrical object with expected changes in the effective index of refraction in both the horizontal and vertical directions (see figure 7).

The source-to-detector and source-to-grating distance were for this measurement 890 mm and 405 mm, respectively. The approach has been tested for various geometrical magnifications (there is no principal restriction in placing the investigated object in front of or behind the 2-D grating) as well as for various X-ray spectra (from quasi-monochromatic radiation of the K-alpha line of a Cu-Be target spot to a broad polychromatic spectrum of a W-Be target spot at 70 keV). An X-ray tube FXE 160.50 FeinFocus with spot of Gaussian shape (sigma \( \sim 1 \mu m \)) equipped with a changeable anode was used. The measurement was performed with the Timepix detector [23] operated in counting mode. Parameters of the grating: size of the square-shaped openings was 25 \( \mu m \), periodicity of the grating was 50 \( \mu m \) (i.e., the width of the gold parts in between was 25 \( \mu m \)). The thickness of the gold layer electroplated on a 100 \( \mu m \) thick glass base was 30 \( \mu m \).

4 Conclusions & future work

In this contribution, we have demonstrated that the novel XPCI approach utilizing a single absorption grating and a hybrid semiconductor pixel detector is an imaging tool with great application potential, e.g., in medicine, biology or material research, because both absorption and clear quantitative phase gradient information are acquired in a single exposure.
Figure 7. Results of the proof-of-principle experiment performed for the proposed 2-D sensitive approach: (a) absorption image (b) phase gradient image measured in the horizontal direction, (c) phase gradient image measured in the vertical direction, (d) photograph of the testing object (2 cylinders of PMMA of 2 mm diameter fixed together by a piece of double-sided tape). All images (a,b,c) were retrieved from a single exposure data. Image taken with a non-filtered tungsten spectrum at 50 keV. The cross sectional views profiles (e) and (f) indicated by the yellow lines in (b) and (c), respectively, show good agreement with the theoretical prediction.

As a direct extension of this 1-D single grating approach, the novel 2-D sensitive XPCI method has been introduced. In a single exposure, phase gradient images in two perpendicular directions together with the conventional attenuation image are measured. The application of the 2-D phase gradient information in relation to the phase wave-front integration is underway.

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