X-ray phase contrast imaging using a broadband X-ray beam and a single phase grating used in its achromatic and propagation-invariant regime.

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Abstract. Recently, Onera developed a new interferometer for X-ray phase contrast imaging. This device uses a single phase grating and takes advantage of the incident light spectral bandwidth to create an achromatic and propagation-invariant pattern. This very simple setup produces highly contrasted interferograms after a certain distance of propagation. Our first quantitative images are presented in this paper and the performances of the device are discussed.

1. Introduction
X-ray radiography based on absorption contrast is one of the oldest and most convenient techniques for medical and imaging diagnosis and for many industrial applications. However, it is completely inefficient when the components of the studied object have similar absorption properties. X-ray phase contrast imaging (XPCI) can overcome this limitation. The cross section for elastic scattering of hard X rays in matter, which causes a phase shift of the wave passing through the object of interest, is usually much greater than that for absorption. Thus, using the phase shift information instead of the absorption can substantially increase the contrast of images. Consequently, several hard X-ray phase contrast imaging methods have been developed during the last decades [1]. Grating based techniques [2] are among the most promising ones and increasing attention has been devoted to them.

Even the most recent grating based XPCI [3] setups rely on the Talbot effect and require the use of at least two gratings. Such devices have been tested and validated on synchrotron radiation beam lines, but also on standard X-ray sources. However, the drawbacks inherent to the use of two gratings prevent their industrialization. Some researches with a 2D single absorption grating, a Hartmann mask, have already been realized and yielded to interesting results [4]. In this context, we decided to develop an XPCI technique which uses a single phase grating only. The single phase grating interferometer (SPGI) relies on multi-wave lateral shearing interferometry (MWLSI) [5] and continuously self-imaging gratings (CSIG) [6] enabling the creation of an achromatic and propagation invariant regime known as the panchromatic effect [7]. These techniques are developed at Onera since 1991 and lead in 2004 to the creation of the French company Phasics, which commercializes high quality wave front
sensors and phase contrast microscopes for the visible range [8]. In the X-ray domain, the existence of the panchromatic regime has been demonstrated recently [9].

In this paper, we will present our first quantitative phase contrast images and discuss the SPGI performances.

2. Single phase grating X-ray interferometer

To demonstrate the interest of our technique in the X-ray regime, we used the bending magnet radiation of the SOLEIL Metrology and Tests Beam Line [10]. The white beam coming from the source was used without any spatial or spectral conditioning, and propagated in free space down to the beam line end station. The device was implemented, at atmospheric pressure, behind a 150 µm thick CVD diamond window and a 1.5 m air path, thus leading to a useful spectrum between 5 and 50 keV at the grating position.

Our interferometer is composed of a single phase grating and a dedicated indirect detection system. The phase grating is a gold chessboard structure with 3 µm height and 6 µm pitch, grown on a 300 µm thick silicon substrate. The indirect detection system is composed of a 20 µm thick YAG: Ce crystal allowing for conversion of the X-rays to visible light. The scintillator is coupled with a (×5.5) magnification optical system onto a highly sensitive cooled 14 bits visible CCD camera (PCO 2000s), with 2048×2048 pixels and 7.4 µm per pixel. The resulting effective pixel size was 1.3µm in the detection plane. Figure 1 shows the experimental setup as implemented. The distance S between the source and the grating was 32 m. The distance D between the grating and the detection plane was 40 cm and the distance L between the grating and the sample was 20 cm.

![Figure 1. SPGI experimental layout on the SOLEIL Metrology and Tests beam line](image)

Bi-dimensional grating interferometry belongs to the class of multi-wave lateral shearing interferometry. The grating acts as a beam splitter which diffracts two orders of propagation in the two periodicity directions of the grating. However, the transmission of the device is not a perfect 2D sinusoid. As a result, parasitic orders are diffracted. In reference [9], we demonstrated that under large spectral bandwidth illumination, a phase chessboard grating can minimize the energy dissipated in the parasitic orders and offers a good approximation of a 2D sinusoid transmission. After a certain distance of propagation called panchromatic distance, it creates a fringe pattern that is achromatic and propagation invariant and theoretically enables wave front analysis in any plane. We have controlled that the sample does not modify the X-ray spectrum so that the panchromatic distance is not modified by the introduction of our sample. Thus, the detector always remains in plane where the fringe pattern is achromatic and propagation invariant. We used these particular conditions to obtain our first images with the SPGI.
3. Quantitative phase contrast imaging

All grating based XPCI devices are not sensitive to the phase of the signal itself, but to its gradients. That’s why we used a canonical object with well known gradients to estimate how precisely gradients can be measured. The sample, described in figure 1, was a silicon wafer chemically attacked in the two directions x and y. As a result, we obtain a plane object with two slopes perfectly controlled in the two directions where the interferometer is gradient sensitive. Figure 2 shows the interferograms obtained successively with and without the sample in the beam path. The region of interest is limited to a square area of 512×512 pixels, corresponding to 1/16 of the field of view.

![Interferograms](image)

**Figure 2.** (a) Raw interferogram with sample (b) Reference interferogram without sample (c) Enlarged part of the fringe pattern

Figure 2.c represents the fringe pattern. Contrast of the fringe pattern is about 0.32, and appears sufficiently high to allow phase contrast imaging. Figure 3 shows the gradient reconstruction along the X and Y directions.

![Gradient Reconstructions](image)

**Figure 3.** (a) Phase gradient along direction X (b) Phase gradient along the direction Y

We can observe on these two reconstructions that the area corresponding to the slopes of the sample have a different contrast than the rest of the image and are so well detected. The contrast is equal to 0.27 in figure 3.a and 0.55 in figure 3.b. The contrast is better in figure 3.b because the direction Y corresponds to the maximum of coherence of the source. The signal to noise ratio will be computed on the final phase map reconstruction performed with these two gradients.

Figure 4 represents the final reconstruction. We used a new type of non-iterative boundary artifact free algorithm in order to reconstruct the wavefront from its derivatives. This algorithm is described in the reference [11]. Figure 4.a represents the phase map reconstruction and figure 4.b is a scanning electron microscope (SEM) image of the area of interest of the sample. The SEM measurement gives a value of the height of the step of the sample equal to 211 µm, leading to an optical path difference of nearly 0.22 nm. On the phase image, we notice that the height of the step is equal to 1.1 A.U. Signal to noise ratio in the reconstructed image is evaluated by taking the standard deviation of a 20 by 20 pixels region, in the slope, after subtraction of the best slope, compared with the restituted height of
The step. It gives a value higher than 250, which is a conservative value, as it is assumed that the observed sample, a chemically attacked Si wafer, is perfect.

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{fig4.png}
\caption{(a) Reconstructed phase map (b) SEM measurement}
\end{figure}

4. Conclusion

We presented in this paper a new type of X-ray 2D grating based interferometer that can perform phase contrast imaging. Whereas a lot of these interferometers require the use of two gratings and are sensitive to the use of polychromatic and divergent beam, this new device uses a single phase grating and takes advantage of the spectral bandwidth of the source to create an achromatic and propagation invariant pattern; it enables wave front analysis or phase contrast imaging on a large and continuous range of planes after the grating. We performed quantitative phase contrast imaging of a canonical object to characterize the performances of our SPGI. The accuracy of measurements and the quality of the reconstructed phase map obtained with this simple sample are a promising result for this new device and represent a step further in the use of phase contrast imaging as an industrial product. The research described here has been supported by Triangle de la Physique.

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