Towards X-ray differential phase contrast imaging on a compact setup

T. Thüring^{a,b,*}, P. Modregger^{a,d}, B. R. Pinzer^a, Z. Wang^a, S. Rutishauser^{b,c}, C. David^c,
T. Grund^e, J. Kenntner^e, M. Stampanoni^{a,b}

^aSwiss Light Source, Paul Scherrer Institute, Villigen PSI, Switzerland

^bInstitute for Biomedical Engineering, Swiss Federal Institute of Technology, Zurich,
Switzerland

^cLaboratory for Micro- and Nanotechnology, Paul Scherrer Institute, Villigen PSI, Switzerland

^dCenter for Biomedical Imaging (CIBM), University of Lausanne, Switzerland

^eKarlsruhe Nano Micro Facility (KNMF), Karlsruhe Institute of Technology (KIT), Karlsruhe,
Germany

ABSTRACT

A new imaging setup, aimed to perform differential X-ray phase contrast (DPC) imaging with a Talbot interferometer on a microfocus X-ray tube, is demonstrated. The main features compared to recently proposed setups are an extremely short source to detector distance, high spatial resolution and a large field of view. The setup is designed for an immediate integration into a industrial micro CT scanner. In this paper, technical challenges of a compact setup, namely the critical source coherence and divergence, are discussed. A theoretical analysis using wave optics based computer simulations is performed to estimate the DPC signal visibility and the size of the field of view for a given setup geometry. The maximization of the signal visibility as a function of the inter-grating distance yields the optimal grating parameters. Imaging results using the optimized grating parameters are presented. The reduction of the field of view, being a consequence of the high beam divergence, was solved by fabricating new, cylindrically bent diffraction gratings. The fabrication process of these gratings required a change of the currently used wafer materials and an adaption of the manufacturing techniques. The implementation of the new setup represents a major step forward for the industrial application of the DPC technique.

Keywords: Phase contrast imaging, grating interferometer, compact setup, high resolution, curved gratings

1. INTRODUCTION

X-ray phase contrast imaging has gained high relevance in the past due to the impressive contrast enhancement in the hard X-ray regime. Instead of recording the attenuation of X-rays by a sample, phase contrast methods measure the phase shift of the passing wave. Particularly in biomedical imaging applications, the contrast can dramatically be enhanced compared to conventional absorption based imaging.^{1,2}

In the past few years, various phase contrast techniques have been proposed. They can be divided into propagation based methods,^{3–5} interferometric methods^{6–8} and crystal analyser based methods.^{9–13} Many of these methods favour the use of highly coherent X-rays, which are provided by a synchrotron source. Among these techniques, the recently developed grating interferometer method has the advantage to be highly insensitive to temporal coherence and thus it is well suited for the application with conventional X-ray tubes. The method, known as differential phase contrast (DPC) imaging, allows for extracting absorption, phase and dark-field signals simultaneously. Depending on the number of gratings used, there are mainly two different setup configurations.

The Talbot interferometer consists of two gratings, a phase grating g_1 and an absorption grating g_2 (Fig. 1a). In this configuration, a coherence length of $\xi_s = \lambda l / w \geq p_1$ is required, where p_1 is the period of g_1 , l is the source-to- g_1 distance and w is the source size. The grating period p_1 is typically a few microns and therefore,

*E-mail: thomas.thuering@psi.ch, Telephone: +41 563103713

a coherence length in the order of $\xi_s \geq 10^{-6}$ m is required. With photon energies in the hard X-ray range ($\lambda \approx 10^{-11}$ m) and a setup length in the order of 1 m, the required spot size of the source becomes $w \approx 10^{-5}$ m. Apart from synchrotron sources, this requirement can only be met by microfocus tubes.

An alternative is the Talbot-Lau configuration, where a third grating with absorbing structures, g_0 , is used to generate an array of individually coherent, but mutually incoherent sources. This technique decouples the spatial resolution from the spatial coherence and is therefore well suited for conventional X-ray sources.¹⁴ The requirement for the coherence length becomes $\xi_s = \lambda l / \gamma_0 p_0 \geq p_1$ and thus, ξ_s is no longer dependent on the source width w , but only on the period p_0 of the source grating and the duty cycle γ_0 . The maximal resolution in the Talbot-Lau setup is still given by $w d_s / l_s$, where l_s is the source-to-sample and d_s is the sample-to-detector distance (see Fig. 1).

A compact DPC setup is of high industrial interest for the application of phase contrast imaging on commercially available micro CT scanners. Compact micro CT scanners achieve high resolution by using geometrical magnification. This requires a minimal source size w , provided by microfocus tubes. High resolution DPC imaging on a microfocus tube was first reported by Engelhardt et al.¹⁵ However, due to the low power of the tube and the relatively long source-to-detector distance, the photon flux for this setup was rather low, leading to relatively long exposure times.

In this paper, a new DPC setup, based on a Talbot interferometer and a microfocus X-ray tube, is presented. The main features are an extremely compact setup length, high resolution and a large FOV. Due to the short setup length, we expect the exposure times to be considerably reduced.

For the realization of a compact Talbot interferometer setup with a microfocus tube, mainly two problems, the critical beam coherence and the high beam divergence, are encountered. Here, we report on the solution of these problems, involving the optimization of the inter-grating distance based on computer simulations and the fabrication of deformable gratings.

Figure 1. a) Schematic of a compact DPC setup with high magnification. g_1 is a phase grating, which periodically shifts the phase of the incoming wave by π . g_2 is an absorption grating, acting as a mask for the interference fringes. b) phase stepping curves, obtained in each pixel from the translation of g_2 in x -direction. $\Gamma_{flat}(x)$ is the reference scan and $\Gamma_{meas}(x)$ the object scan. From these curves, an absorption (τ), DPC (φ) and darkfield (σ) signal can be extracted.

2. THEORY AND METHODS

2.1 Talbot interferometer

Fig. 1a schematically shows the Talbot interferometer. The first grating, g_1 , is a phase shifting grating, which periodically introduces a phase shift of π to the beam. This generates an intensity modulation due to the Talbot effect.¹⁶ Maximal interference, or so called Lohmann images,¹⁷ occur at odd fractional Talbot distances d_m^* , given by¹⁵

$$d_m^* = d_m \frac{l}{l - d_m} \quad (1)$$

and

$$d_m = m \frac{p_1^2}{8\lambda}. \quad (2)$$

λ is the wavelength and m is an odd integer corresponding to the fractional Talbot order.

Beam refraction, generated by a sample which is placed in front of g_1 , leads to a transversal shift of the interference pattern at the position of the second grating g_2 . g_2 is positioned at a distance of odd fractional Talbot order and consists of absorbing structures (e.g. gold). The period p_2 matches the period of the interference fringes and therefore, g_2 acts as a mask for these fringes. The transversal fringe shift can be sensed with g_2 by using a phase stepping approach.¹⁸ Moving g_2 in the x -direction leads to an intensity oscillation in every pixel of the detector. The obtained oscillation curve $\Gamma(x)$ (see Fig 1b) is referred to as the phase stepping curve (PSC). An imaging experiment consists of a reference phase stepping scan $\Gamma_{flat}(x)$ as well as a stepping scan with the sample in place $\Gamma_{meas}(x)$. From these two scans, an absorption (τ), differential phase (φ) and darkfield signal (σ) can be extracted by using Fourier analysis of the PSCs. The three signals are given by

$$\begin{aligned} \tau &= \frac{|a_{0,meas}|}{|a_{0,flat}|} \\ \varphi &= \arg(a_{0,meas}) - \arg(a_{0,flat}) \\ \sigma &= \frac{|a_{1,meas}| \cdot |a_{0,flat}|}{|a_{0,meas}| \cdot |a_{1,flat}|}, \end{aligned} \quad (3)$$

where a_i is the i -th Fourier coefficient of the corresponding $\Gamma(x)$.

An important parameter in terms of SNR in a DPC image is the DPC signal visibility, given by¹⁹

$$V = \frac{\Gamma_{max} - \Gamma_{min}}{\Gamma_{max} + \Gamma_{min}}. \quad (4)$$

It represents the normalized amplitude of $\Gamma(x)$ and is dependent on the spatial and temporal beam coherence, the setup geometry and the absorption efficiency of g_2 .

2.2 Beam coherence effects

Low spatial beam coherence leads to blurring in the interference pattern in x -direction (see Fig. 2b). This effect is due to the finite source width and leads to a severe loss in visibility. Weitkamp et al.²⁰ derived an analytical expression for the DPC signal visibility as a function of the full width half maximum (FWHM) w of a gaussian shaped source, given by

$$V = e^{-\frac{\pi^2}{4 \ln 2} \cdot (d \frac{w}{l \cdot p_2})^2}. \quad (5)$$

This equation was derived under the assumption of a sinusoidal interference pattern for infinite spatial coherence, although the true pattern would be rectangular.¹⁹ However this assumption simplifies the calculations to obtain Eq. (5), allowing for a simple but yet important description of the relative dependencies between visibility V , source size w and inter-grating distance d .

It is also important to note that the visibility estimation in Eq. (5) assumes an ideal absorption grating and does not take into account temporal incoherence, which both affect the visibility. Although the Talbot interferometer can be considered achromatic,¹⁸ a broad energy spectrum smears the interference pattern in the beam direction and decreases the visibility (see Fig. 2). In general, the larger the inter-grating distance, the more critical becomes the temporal coherence effect. For a compact setup, we are anyhow restricted to low fractional Talbot orders due to the limited spatial coherence, which is in this case positive. We investigated the relationship between temporal coherence and visibility by a wave-optics based computer simulation approach. The simulations included several aspects found in real conditions such as finite spatial and temporal coherence, X-ray spectrum distributions and gratings properties.

Figure 2. Qualitative examples of interference patterns for a) a highly spatial and temporal coherent beam, b) low spatial coherence and c) low temporal coherence. The effect of spatial incoherence is more significant than the effect of temporal incoherence, as it smears the fringes in x -direction and destroys the visibility at high inter-grating distances. The solid line indicates the first fractional Talbot order distance. In b), there is still some interference at shorter distances. The position of maximum interference is marked with the dashed line.

2.3 Visibility Simulations

In Fig. 2b, the intensity modulations completely vanish for large inter-grating distances d due to the critical spatial coherence. However, moving for a shorter d indicates, that there is still signal left at a certain position (indicated with dashed line). The position of this interference maximum can be found by optimizing the visibility as a function of d .

Fig. 3a shows the simulated visibility versus the inter-grating distance d under monochromatic and polychromatic irradiation. The setup parameters were $l = 0.28$ m, $E_{g1} = 40$ keV, $p_2 = 2.4$ μ m and $h_2 = 60$ μ m (g_2 thickness). Furthermore, the focal spot size of the source was assumed to be $w = 5$ μ m (FWHM). For the polychromatic simulation, the energy spectrum of Fig. 3b was taken. It was calculated with the X-ray tube spectrum software SpekCalc,²¹ using a W-target and a tube voltage of 67 kVp. Apart from the 200 μ m thick grating wafers, no filtering was applied to the spectrum. The characteristic lines around 10 keV were filtered out.

Figure 3. a) Visibility versus inter-grating distance d for mono- and polychromatic irradiation. The given parameters are $l = 0.28$ m, $E_{g1} = 40$ keV and $p_2 = 2.4$ μ m. The structure height of g_2 was set to $h = 60$ μ m. b) applied spectrum for the simulation with polychromatic irradiation with a W-target tube, operating at 67 kVp

For the given setup parameters, the first fractional Talbot distance ($m = 1$) would be at $d = d_1^* = 7.35$ cm (marked in Fig. 3 with dashed line). Under perfect coherence conditions, the visibility would reach the maximum at this position. The curve in Fig. 3a clearly shows, that d_1^* is no longer an optimal inter-grating distance. The new maximum is shifted to the left towards a shorter d . For monochromatic irradiation, this maximum is at $d_{max,mono} = 4.6$ cm, whereas for polychromatic irradiation, it is located at $d_{max,poly} = 3.6$ cm. In other words, the maxima are no longer located at exact odd fractional Talbot orders, they lie at $m_{max,mono} \approx 0.58$ and $m_{max,poly} \approx 0.43$.

It is also important to point out that for every simulation distance d in the graph of Fig. 3a, a different value of p_1 was calculated. The experimental validation of this curve would require the fabrication of many phase gratings, resulting in an unaffordable manufacturing and financial effort.

2.4 Beam divergence effect

For a compact setup, a large beam divergence allows for a large FOV, even if the geometrical magnification is high. The problem of a high beam divergence on a short setup is the planarity of the gratings. The gratings of currently available fabrication techniques are based on planar substrates (e.g. Silicon)^{22,23} and the structures generally have a high aspect ratio, given by

$$AR = \frac{h}{p}. \quad (6)$$

h is the structure height and p the period of the grating. The duty cycle of the grating is assumed to be 0.5. In particular for the absorption grating, where the structures heights need to be as large as possible, AR becomes very high. X-rays penetrating the grating structures at angles close to or higher than $1/AR$ do not “see” a well shaped grating. This leads to a reduction of the interference effect downstream of g_1 and to a distorted absorption mask at g_2 . The result is a rapid decay of the DPC visibility at these angles. Fig. 4 illustrates this effect.

Figure 4. X-rays penetrate the grating with an angle larger than $1/AR$. This leads to a rapid visibility decay at these angles and results in a reduction of the FOV

The loss of visibility at high angles is equivalent to a reduction in FOV. Fig. 5 shows a simulation of this effect and a corresponding measurement. The total setup length was extremely compact with $s = 25$ cm. The inverse aspect ratios were $1/AR_{g_1} = p_1/h_1 \approx 0.16$ and $1/AR_{g_2} = p_2/h_2 \approx 0.05$. The smaller value of $1/AR_{g_2}$ clearly shows that g_2 represents the critical grating. In Fig. 5, the detector position where the incident beam angle corresponds to $1/AR_{g_2}$, is indicated with the dashed line. The visibility reaches a minimum at this position and even starts to drop before. The FOV in this setup is reduced to approximately 1.5 cm.

Figure 5. Simulated and measured visibility curve versus the detector position. The decay of the visibility occurs at the position where the incident angle corresponds to $1/AR$ of the absorption grating (indicated with the dashed line).

A possible solution to this problem is the fabrication of cylindrically bent gratings, where the center axis of the curvature intersects with the focal spot of the source. Fig. 6 shows the schematic of a setup using curved gratings.

Figure 6. Schematic of a compact DPC setup with cylindrically bent gratings

The fabrication of bendable gratings is a challenging task. In collaboration with Karlsruhe Nano Micro Facility (KNMF), a study of possible wafer materials was carried out. The investigation aimed at finding materials, which would be suitable for an X-ray lithography process and at the same time have the property to be deformable. Titanium was now found to be the most promising wafer material with the required characteristics. The substrate material and the corresponding process allow a bending radius below 50 mm.

3. RESULTS

Fig. 7 shows the results of a radiographic absorption, DPC and darkfield measurement of a wasp using planar gratings with an optimized inter-grating distance. The tube voltage was 55 kVp. The total setup length was $s = 32$ cm and the fractional Talbot order was $m = 0.83$. The number of phase steps was 8 and the exposure time was 8×10 s = 80 s. The pixel size of the camera was $75 \mu\text{m}$. The exposure time was rather long, which was mainly because of the camera. The camera was a single photon counting device and not optimized for the high energies. Fig. 7 also shows a 4 fold geometrically magnified image of the head of the wasp, having an effective pixel size of $19 \mu\text{m}$.

Figure 7. Images of a wasp, taken with a DPC imaging setup with a total setup length of $s = 32$ cm. The images show a) the absorption, b) dark field and c) DPC image, d) a 4 fold geometrically magnified DPC image of the wasp head.

In order to compare the performance of curved gratings, visibility maps using planar and curved gratings were acquired. Fig. 8 shows the result of this experiment. As expected, the visibility with planar gratings rapidly decays in the off-center region of the detector. The result of the bendable gratings is very promising, as the visibility map is extremely homogeneous over the entire FOV.

4. CONCLUSION

A new DPC setup on an extremely compact setup distance, providing high resolution and a large FOV has been demonstrated. Achieving high resolution requires the use of a low power microfocus tube, which does usually not provide high photon flux. However, due to the short setup length, exposure times could be kept relatively short.

Figure 8. Visibility maps for a) a pair of planar gratings and b) a pair of curved gratings. The visibility with planar gratings decays rapidly in the off-center region, whereas the curved gratings generate a homogenous visibility over the entire FOV.

Critical beam coherence and high beam divergence represented the main challenges for a compact setup. It was shown that critical beam coherence conditions led to a reduction of the signal visibility. An examination of the visibility as a function of the inter-grating distance by means of computer simulations showed, that the inter-grating distance can be optimized. Thereby, the optimal inter-grating distance is no longer located at the first fractional Talbot order, it was shifted towards shorter lengths. By optimizing the inter-grating distance, the visibility could significantly be increased.

A high beam divergence, being a result of the compact setup length, led to a reduction of the FOV due to the planar shape of the gratings. This problem could be solved by using cylindrically bent gratings. The fabrication of deformable gratings could be realized by using Titanium as a substrate.

The optimized, bendable gratings allow for performing DPC imaging on a short setup length. This development was crucial for the integration of the DPC method in commercial micro CT scanners. The availability of DPC as a standard tool for radiographic and tomographic applications in industrial devices represents a major step forward in radiology.

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