Cascade Talbot–Lau interferometers for x-ray differential phase-contrast imaging

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Abstract

X-ray Talbot–Lau interferometer (TLI)-based differential phase-contrast imaging (DPCI), owing to its potential capability of multiple contrast mechanisms and adaptability for variety of samples, has attracted widespread attention in the last decade. However, the fabrication of the absorption grating, an indispensable element in a conventional TLI, presents a significant challenge for practical applications. Here, we report on a cascaded TLI (CTLI) configuration for DPCI, i.e. a TLI followed by an inverse TLI (ITLI), through which the small-period high-aspect-ratio (HAR) absorption gratings (analyzing gratings and source gratings in the conventional TLI and ITLI, respectively) could be omitted. Instead, the large-period absorption gratings (generally tens of microns) are allowed to be employed, which significantly relieves the grating fabrication difficulties, especially for the large-area ones. The success of our CTLI configuration is validated by the observation of moiré fringes, and the resulting phase-contrast and visibility-contrast images for DPCI. Moreover, our CTLI configuration is promising to yield magnified interference fringes capable of being detected directly by commonly used large-area detectors.

Keywords: x-ray imaging, phase contrast, cascade interferometer, grating

(Some figures may appear in colour only in the online journal)

1. Introduction

The last decade has seen the development of x-ray differential phase-contrast imaging (DPCI) [1–6]. Talbot interferometers (TIs) have been used into DPCI to image the weak-absorption samples by measuring the phase shift imposed on a spatially coherent illumination, typically a micro focus x-ray source or a synchronous radiation source [1]. Afterwards, a modification to TI by introducing a source grating (multi-slit), forming what known as Talbot–Lau interferometer (TLI), makes conventional x-ray tube available whereby the moiré patterns derived from those slits overlap constructively [2, 3]. This offers DPCI an overwhelming brighter source than micro focus x-ray source but independent of synchronous radiation sources, and able to bring multi-contrast images (including absorption, phase, and dark-field images) [3–6]. Some potential applications of such DPCI include early diagnosis of lesions, characterization of polymers in materials science, non-destructive testing in industry, and guaranteeing safety [7–10].

The phase sensitivity of conventional x-ray TIs or TLIs are dependent on the measurement of sheared interference fringes introduced by samples [1, 11]. The spatial coherence condition of the light source in the TIs or TLIs and the overall compactness of the system typically require the use of a micron-scale phase grating as the beam splitter [3]. As a result, the resulting self-image also has the same magnitude, which is too small for a detector to resolve. Therefore, it is

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necessary to put an absorption grating in front of the detector to sample the generated interference fringe and record the resulting moiré fringes. Inevitably, such a sampling grating is a high-aspect-ratio (HAR) structure, and its fabrication involves significant challenges, particularly when a large area is desired for practical applications [12–14], e.g. 95% modulation of 40 keV x-ray photons requires a 120 μm-thick Au film to block or transmit x-rays through the gratings (or even a greater thickness is necessary when using a bismuth film) [15].

In order to avoid the use of large-area absorption gratings and the challenges of their fabrication, an inverse TLI (ITLI) configuration was presented, whose level of magnification was so large that the interference fringes could be recorded directly by a detector [16, 17]. However, such an ITLI configuration requires a smaller separation between the source and the phase grating, and consequently, a source with an even smaller emission size than that used in the TLIs is required for an acceptable spatial coherence value of the illuminating source. Thus, two issues need to be addressed for such configurations to be used for practical applications: (i) the fabrication of source gratings with reduced periods and increased aspect-ratios (which can be an even greater challenge, even though their area is reduced); and (ii) the development of a special x-ray source with a structured anode whose period and emission area are of the order of a few microns. The former has not been reported with a compact system to date; however, the latter has been achieved by a compromise of x-ray photon energy and source power capacity [18].

Recently, Miaoz et al implemented an x-ray DPCI using the phase moiré effect by a polychromatic far-field interferometer, in which they employed a single slit (70 μm) source and three small-period phase gratings (399 nm and 400 nm) without the need of absorption gratings, showing an increase in sensitivity and x-ray dose efficiency [19]. However, it would be difficult to achieve so small-period a structure within a large-area. Then, an alternative phase grating cascaded scheme was proposed to avoid the use of large-area and HAR absorption gratings, where the illumination was performed only by a micro focus source [15]. Up to now, no DPCI using above schemes was reportedly implemented with large-area and large-period absorption gratings, and high-brightness radiation at high photon energies.

In this paper, we present a modification of a cascaded TLI (CTLI) configuration for DPCI, which differs from both the methods above in source, and no small-period HAR absorption gratings is necessary. We demonstrate that an ITLI-based DPCI can also be achieved through the use of a conventional x-ray source and a large-period source grating. To do so, we designed a symmetric TLI and ITLI cascaded configuration, in which the TLI (comprising an ordinary x-ray source, source grating, and phase grating) offers micron-scale periodic structure illumination, and the ITLI provides large-period interference fringes. We show that a large-period absorption grating can also be used as the sampling grating, relieving the difficulties in the fabrication of large-area and HAR sampling gratings.

2. Methods and experiments

In a TLI, the following Lau condition holds:

\[ \frac{\alpha}{p_1} = \frac{1}{p_0} + \frac{1}{p_2} \]  

(1)

where \( p_0 \), \( p_1 \), and \( p_2 \) are the periods of the source grating \( G_0 \), phase grating \( G_1 \), and analyzer grating \( G_2 \) (self-image), respectively. The constant \( \alpha \) is equal to 1 or 2, depending on whether a \( \pi/2 \) or \( \pi \) phase grating is used [2]. The Talbot distance, \( R_2 \) (relative to the phase grating \( G_1 \)), can be written as:

\[ R_2 = \frac{k p_1^2}{\lambda} \left( R_1 + R_2 \right) \]  

(2)

where \( \lambda \) is the wavelength of the x-rays, \( R_1 \) is the distance from \( G_0 \) to \( G_1 \), and \( k \) is a coefficient determined by the grating’s phase shift that falls into two categories depending on the choice of phase grating: \( k = 1/2 \), 3/2, 5/2, ..., for a \( \pi/2 \) phase grating, or \( k = 1/8 \), 3/8, 5/8, ..., for a \( \pi \) phase grating [3]. We note that (2) may be transformed into the form,

\[ \frac{1}{R_1} + \frac{1}{R_2} = \frac{1}{f} \]  

(3)

with the substitution,

\[ f = \frac{k p_1^2}{\lambda}. \]  

(4)

It is worth highlighting that the simultaneous exchange of \( R_1 \) and \( R_2 \) in (3), and of \( p_0 \) and \( p_2 \) in (1) implies that a large-period self-image (fringes) can be achieved using a small-period source array. This result was the original basis for the ITLI configuration; however, a question remains that how to introduce a coherent illuminating source into this ITLI configuration in a low-cost manner.

A heuristic idea arising from the similarity of (3) to lens imaging is that the coherent illuminating source could be the TLI’s self-image. Motivated by this insight, we designed a CTLI, shown schematically in figure 1, in order to validate our hypothesis that the interference fringe could be transmitted and magnified, just as how the same can be achieved for an image in an optical lens system. The setup presented here can also be considered as two conventional TLIs sharing a ‘secondary source’ between them. Functionally, the source grating \( G_0 \) modulates the incident beam to be coherent; thus, the interference fringes of the self-image form a downstream behind the first phase grating \( G_1 \). These interference fringes then serve as an illuminating source for the ITLI, which is able to generate magnified fringes large enough to be resolved by a detector. Consequently, in a TLI, the disadvantage of the small period of the interference fringes can be an advantage served as a source with a characteristic of enough coherent length for an ITLI, under the condition of constructing a relationship between the fringes and the source according to equation (3). In our CTLI assembly, we chose a symmetrical configuration for the TLI and ITLI components using only two types of gratings (noting that a conventional TLI uses three kinds of gratings). The geometry of our setup was as follows: \( R_1 = R_2 = 0.763 \) m,
$R_2 = R'_1 = 0.101 \text{ m}$, and $p'_1 = p_1$, where $R'_1$ and $R'_2$ are shown in figure 1, and $p'_1$ is the period of the phase grating $G'_1$. The source grating $G_0$ (duty cycle 0.25) was fabricated by micro-casting in 5-inch silicon wafers using bismuth as the absorption material. Since a $\pi$ phase grating leads to a more compact system than a $\pi/2$ one, the phase gratings were prepared by deep reactive ion etching (DRIE) with a $\pi$ phase shift for x-rays centred at a wavelength of $\lambda = 0.0443 \text{ nm}$ (28 keV). Further details regarding the methods and technologies used in the fabrication process are available in our previous works [12, 20]. The parameters of the gratings used in the configuration presented here are listed in table 1.

For our imaging experiments, a voltage of 40 kV (photon energy centred at 28 keV) and current of 4 mA were imposed on a conventional x-ray tube with an effective focal spot size of $1 \times 0.8 \text{ mm}^2$. According to our ‘secondary source’
3. Results and discussions

At the very beginning, we tried to correlate the characteristic of our CTLI by directly observing the interference fringes. Despite the use of a high-resolution x-ray detector with a pixel size of 5 μm (Crytur CRYCAM 3.1) and an exposure time of 200 s, we failed to record the interference fringe $G_2'$ in figure 1. This was likely due to the mismatch between the x-ray photon energy and scintillator thickness of the detector, which led to too poor a capture efficiency for high-energy photons, i.e. we believe a poor signal-to-noise ratio (SNR) prevents any fringe information from being displayed. However, if another absorption grating (fabricated using the same procedure described above, i.e. with a period of 24 μm, 0.5 duty cycle, and a 130 μm trench filled with bismuth) is placed at the position of $G_2'$ and followed by an x-ray flat panel detector, interference fringes can be observed, as the one shown in figure 2 for a single exposure time of 3 s and a pixel size of 74.8 μm.

Figure 2 indicates that the effective area of the moiré fringes is restricted by both the second absorption grating (diameter: 10.5 cm) and the detector (11.5 × 6.5 cm²). Furthermore, by measuring the pixels along the transverse line, a visibility of approximately 17% was obtained. A direct cause-and-effect relation between the recorded fringe pattern and the phase gratings is readily confirmed by removing one (or both) of the two phase gratings, in which case no fringes appear. The fringes are also observed to vary in period and visibility with the relative orientation of the two phase gratings, and particularly with the slit direction of the second absorption grating. Consequently, we deduce that what we acquire with this configuration is actually the moiré fringes generated by the second absorption grating and the self-image of the second TLI at position $G_2'$. Therefore, with the ‘secondary source’ assumption, we can estimate the approximate self-image period of the second TLI from the fringes at $G_2'$.

Kept the high voltage and the tube current unchanged, the orientation of the second phase grating was scanned perpendicularly to the grating slit, and at each step of the scanning process, the intensity of one pixel of the detector was recorded. The scanning process covered one full period of the grating (5.6 μm) in 28 steps. After each step, the image was sampled with an exposure time of 10 s. The resulting intensity oscillation curve acquired from this process is shown in figure 3, where the blue circles represent the intensity of chosen pixel in each image. These circles were connected directly using a blue line. In view of their fluctuant that introduced by the noise from this imaging system, so its polynomial fitting curve has been provided in a red line. We see that the curve shows no difference to that obtained from a conventional TLI configuration [5, 21], and therefore, we can retrieve phase-contrast images using the same method as that for a conventional TLI configuration.

We also investigated the dependence of the visibility of the moiré fringes on the position of the second absorption grating which is fixed to the detector. The position $R_2' = 0.763$ m was nominated as the theoretical zero point, at which the second absorption grating should be ideally located. The operation parameters of the x-ray tube were as previously described, only now with an exposure time of 3 s. The visibility was recorded with respect to the detector and absorption grating’s separation along the optical axis, for gratings positions both upstream and downstream of the zero point. The scanning covered a range of over 90 mm in steps of 4 or 5 mm. From the recorded images, we could determine the variation in visibility with each step, as shown in figure 4. The highest visibility of 17.4% occurs at the zero position and the visibility decreases as the absorption grating shifts away from this zero position. We found that the moiré fringe visibility was greater than 10% for a wide range of grating positions, spanning a deviation from the zero position of −17 mm to 12 mm. It is also worth noting that the visibility varies asymmetrically when the absorption grating is placed in front of or behind the zero point, which might be attributed to the photon energy distribution.

Finally, in order to test the feasibility and capability of our x-ray CTLI arrangement, a DPCI experiment was conducted using the configuration presented above, using a charge-coupled device camera (Spectral Instruments Inc., 4096 × 4096 pixels, 9 μm/pixel) coupled with a CsI(Tl)-scintillator (thickness: 400 μm) through a double-amplification fibre optical tape as the detector. A voltage of 40 kV and current of 4 mA were imposed on the x-ray tube and the exposure time was set to 60 s, and the effective field of view was approximately 70 × 70 mm². A standard 4-step phase stepping procedure was used to retrieve multi-contrast images of a lemon, and the resulting images are shown in figure 5.
4. Conclusions

This paper presents our efforts in improving an ITLI assembly in order to achieve a practical application of the DPCI technique. Through the proper insertion of a specific phase grating, we are able to transfer a conventional TLI into a CTLI configuration while maintaining a conventional x-ray tube. Measurements of the resulting interference fringes and imaging experiments validate our hypothesis of the ‘secondary source’ and demonstrate the feasibility of the x-ray CTLI for DPCI. Moreover, the oscillation of the intensity and the successful acquisition of phase-contrast and visibility-contrast images indicate that the CTLI acts like a single TLI. Although one more phase grating attenuates the photon number slightly, the configuration presented here allows large-period absorption gratings to be used as the sampling gratings instead of small-period ones, which significantly eases the grating fabrication difficulties. More importantly, as a supplementary interferential mechanism of the TLI, the assembly reported here allows us to magnify the period of interference fringes to a level that is capable of being directly resolved by a flat panel detector. However, we note that the system length of this configuration with our current elements may be too large for a tolerable SNR to be achieved in all cases. New elements should thus be developed whose parameters are optimized in accord with the principles outlined here. If successful, we believe that the challenges accompanying HAR absorption gratings could be avoided.

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