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2013 J. Phys.: Conf. Ser. 425 052021

(http://iopscience.iop.org/1742-6596/425/5/052021)

Journal of Physics: Conference Series **425** (2013) 052021 doi:10.1088/1742-6596/425/5/052021

# Development of at-wavelength metrology using grating-based shearing interferometry at Diamond Light Source

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**Abstract.** The grating-based shearing interferometer has been established and further developed on B16 at Diamond Light Source. The beamline performances of both an X-ray plane mirror and a compound refractive lens (CRL) have been investigated using this technique. The slope error of the X-ray mirror was retrieved from the wavefront phase gradient, which was measured using two different processing schemes: phase stepping and moiré fringe analysis. The interferometer has demonstrated a high sensitivity with sub-microradian accuracy. Some of the advantages, disadvantages and limitations for the two approaches will also be presented.

## 1. Introduction

Today, advances in X-ray optics permit nanometer-scale resolution and sensitivity and thus are a critical factor in synchrotron development. In-parallel at-wavelength metrology methods, such as grating interferometry, phase retrieval and Hartmann wavefront sensing, [1, 2, 3] are also fully investigated because they can characterize these optics in-situ with a higher sensitivity and accuracy than conventional metrology like long-trace profiling and Fizeau interferometry. The X-ray grating interferometer is one of the most widespread and attractive tools to perform this at-wavelength metrology, due to its compact setup and its moderate requirements on longitudinal and transverse coherence.[1] Such interferometers have been employed for beamline characterization of optical elements such as compound refractive lenses (CRLs), monochromators or X-ray mirrors.[1, 4, 5, 6, 7, 8]. The device consists of a phase grating to split the incoming beam into the -1 and 1 orders, and an absorption grating used as a transmission mask. The absorption grating is necessary to create large moiré fringes that can be resolved by the detector. The measurement of their deviation from the ideal straight geometrical pattern allows the calculation of the wavefront gradient distortion with sub-microradian sensitivity. [4, 9] The fringe distortion is then normally recovered by using phase retrieval algorithms based on Fourier transform. Phase retrieval methods can be classified into two groups. Spatial algorithms use the full image and all the fringes of an image to retrieve the relative phase at each pixel. Temporal algorithms, such as phase stepping, use the movement of a second probe grating to derive the fringes' phase. The phase stepping method requires a minimum of three images in order to derive the phase, while the spatial method requires only a single image. The spatial fringe analysis method was further enhanced with mathematical improvements by the rotating shearing interferometer technique.[6] In this technique, one of the two gratings of the interferometer is rotated to recover accurate experimental parameters without any a priori knowledge.[6] Here, the wavefront aberrations induced by, respectively, a reflecting mirror and a one dimensional CRL were characterized using both the spatial fringe analysis and the phase stepping methods.

## 2. Experimental setup

Measurements were carried out at the bending magnet (BM) beamline B16 at Diamond Light Source.[10] As presented in the setup sketch in Fig. 1, the optic under test and the grating interferometer were mounted on three different motorized towers of an optics test bench. The distance between the source and the lens was 46.6m, and the distance between the phase grating G1 and the absorption grating G2 was 120mm. The energy of the X-ray was set to 15 keV using a silicon double-crystal monochromator (DCM). A 2D X-ray detector with an effective pixel size of 0.9 μm was used. G1 was made from a silicon wafer with a designed pitch of $d_1$ = 4.0 μm. G2 had a design pitch of $d_2$= 2.0 μm and was made by covering the lines of a silicon grating with electroplated gold.[11] The lines of the gratings were oriented in the horizontal direction, giving access to the vertical wavefront gradient.

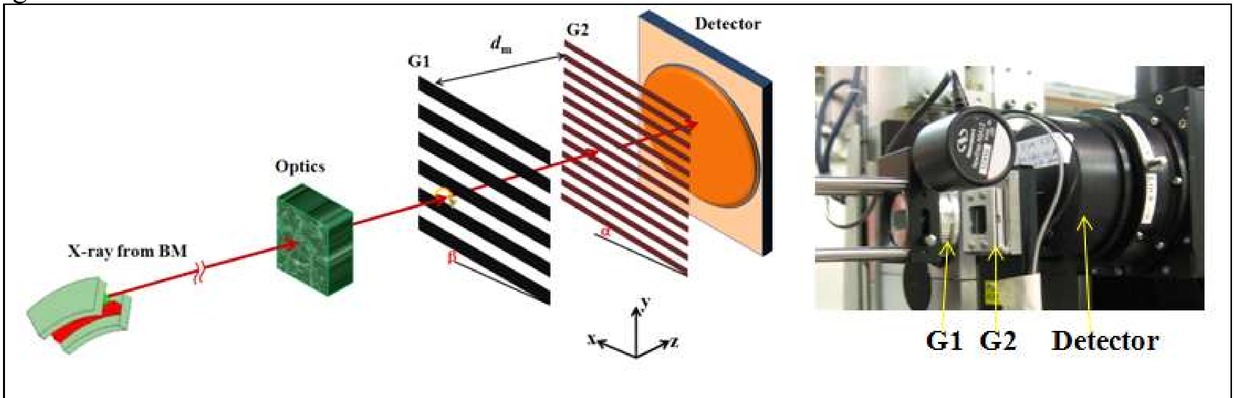


**Figure 1.** Experiment setup and photo of the grating interferometer installed on beamline B16 at Diamond Light Source

## 3. Data analysis

First, the X-ray plane mirror was mounted on the optics stage with a grazing incidence angle of 0.1°, and the wavefront of the reflected beam was measured by the grating interferometer. The two gratings were first aligned parallel to each other and a phase-stepping scan of 32 images was collected by moving the absorption grating. From this image stack, processing with well-known methods permitted accurate recovering of the phase of the recorded moiré fringes.[8] The phase grating was then tilted to generate the moiré fringe that is shown in figure 2a. The fringe analysis method was used to retrieve the wavefront gradient, [6] and the processed interferogram is shown in figure 2b. The vertical incoming beam with 0.17mm height was selected by the entrance slit to illuminate the full mirror length of 100mm. The defects of the flat field were neglected. Therefore, the slope error for the plane mirror is equal to half of the measured wavefront gradient error. The slope errors measured by using the above two methods are compared in figure 2c. The slope error (root mean square) is 0.199μrad and 0.196μrad according to fringe analysis and phase stepping, respectively.

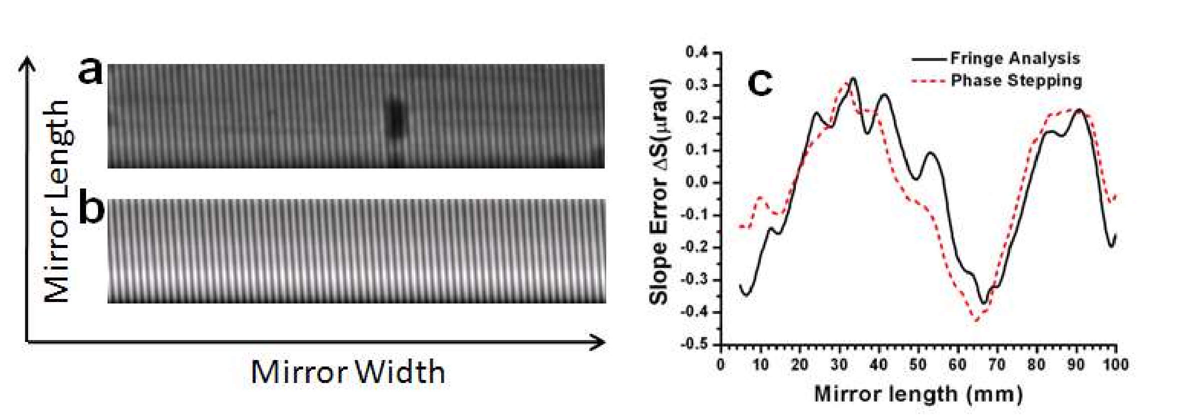


**Figure 2. (a)** Measured and (b) processed interferograms for X-ray mirror, and (c) the retrieved slope errors using fringe analysis and phase stepping method

Another sample under study was a one dimensional (1D) concave parabolic CRL, which was made of beryllium with an aperture of 3mm×1mm. The radius of curvature $R_0$ at the apex of the parabola was 500μm. The lens was mounted so that it focused in the vertical plane, and no focusing optical element was used upstream of the CRL. Figure 3a and b show the fringes before and after insertion of the CRL into the beam. From these, it can be seen that distortions are induced into the fringe pattern by the presence of the CRL. The 1D CRL was also tested using the phase stepping method, in which 96 images were recorded by scanning $G_2$ over 4μm with an exposure time of 400ms. Figure 3c and 3d are the retrieved absorption and phase gradient image for 1D CRL. The phase gradient image has much better contrast than the absorption image, and it shows that the phase gradient is along the vertical direction.

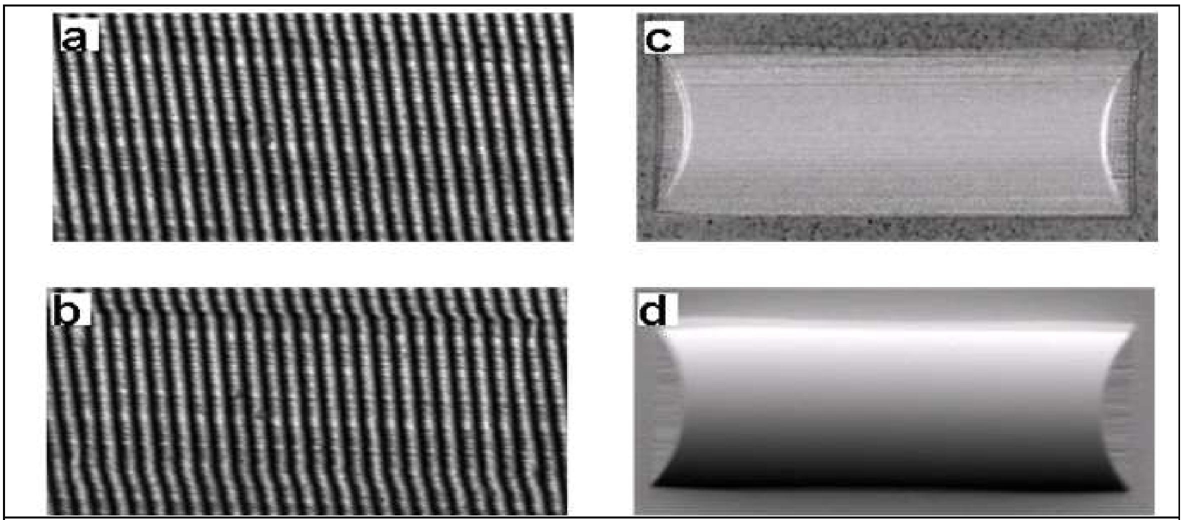


**Figure 3.** The interferogram (a) without and (b) with CRL, and the retrieved absorption (c) and phase gradient images (d) for 1D CRL using the phase-stepping method.

The deflection of the X-rays caused by the CRL oriented at 0° was measured using fringe analysis and phase-stepping methods. The comparison in figure 4a shows that the results are consistent with each other. The effective R, which is the radius of the lens at the parabolic apex as seen under the incident angle of the X-rays, is changed by tilting the lens incident angle $\theta$ around the **y** axis. After the phase-stepping scan was carried out at four different incident angles $\theta$, R was finally derived from the phase gradient (figure 3d).[7] As only one image is required, the moiré fringe analysis method allows fast analysis of the wavefront modification for many different incident angles. As shown in figure 4b, the value of R derived using the phase-stepping method agrees well with that calculated by fringe analysis.

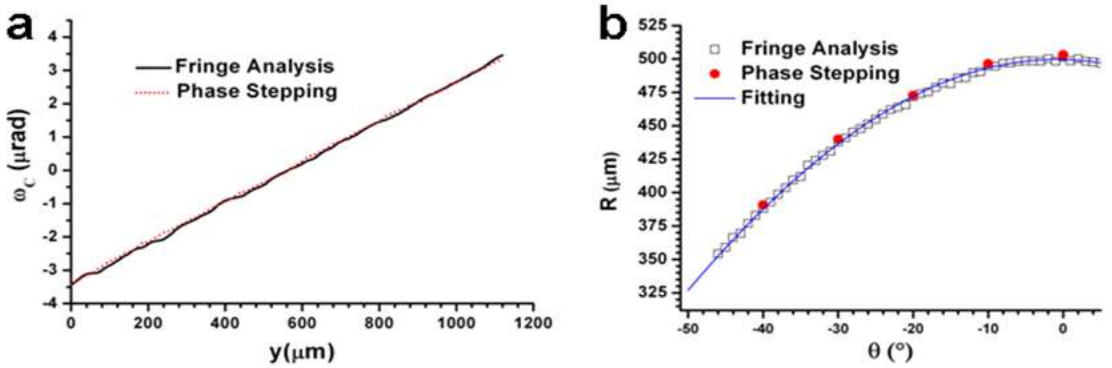


**Figure 4.** (a) The retrieved wavefront slope for 1D CRL using both fringe analysis and phase stepping results. (b) The derived effective radius of curvature R at the apex using the two methods as the CRL tilt the incident angle $\theta$.

## 4. Summary

The grating interferometer allowed us to perform precise and repeatable at-wavelength metrology on refractive and reflective optics. Both the phase-stepping and fringe analysis method were employed at the same time to calculate the beam phase gradient. There are distinct advantages and disadvantages associated with both the fringe analysis and phase-stepping techniques which need to be considered when designing an experiment. The spatial fringe analysis technique is well suited to objects which change quickly in time as only one image is required for the analysis. However, it shows limitations when dealing with high levels of detail and rapidly changing optics. Conversely, the phase-stepping technique has a higher accuracy and spatial resolution. However, the requirement for multiple images prevents this technique from analyzing rapidly changing samples. Therefore, both methods will be needed to cover the very wide variety of metrology requirements.

**Acknowledgments**

This work was carried out with the support of the Diamond Light Source Ltd UK. The authors wish to thank Yong Chu from NSLS II for providing the CRL and Christian David and Simon Rutishauser from PSI for fabricating the gratings used in this experiment. We would like to acknowledge Andrew Malandain for his technical assistance and John Sutter for his help in the correction of this manuscript.

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