ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-THPMF011

FEMTOSECOND LASER ABLATION FOR MANUFACTURING OF X-RAY LENSES AND PHASE CORRECTOR PLATES

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Abstract

The next generation light sources such as diffraction limited storage rings and high repetition rate free electron lasers (FELs) will generate X-ray beams with significantly increased peak and average brilliance. These future facilities will require X-ray optical components capable of handling large instantaneous and average power densities while tailoring the properties of the X-ray beams for a variety of scientific experiments. In this paper we report on research and development of a single crystal diamond compound refractive lens. Diamond lenses presented here are fabricated by fs-laser cutting and subsequent polishing. Grating interferometry measurement data of these lenses had been performed at the Advanced Photon Source (Argonne). Besides the lenses, we fabricated and tested several phase correction plates, a refractive elements designed to correct for cumulative X-ray beam aberrations.

INTRODUCTION

The next generation light sources, diffraction-limited storage rings, will increase the average synchrotron beam brightness by 3 orders of magnitude. For ultrafast experiments, x-ray free electron lasers produce 10 orders of magnitude larger peak brightness than storage rings. It is therefore extremely important to develop next generation x-ray optics for these new light sources. In this project we are looking to develop a next generation compound refractive lens, CRL [1], one of the most popular x-ray optics element. Diamond is a "go to" material for high heat load applications. Single crystal diamond is an excellent material for x-ray optics due to its high x-ray transmissivity and uniform index of refraction. Moreover, CRL performance benefits from the single crystal material of choice for the lens because small angle reflections on defect and voids, typical for polycrystalline materials, are minimized and the x-ray beam quality is preserved. A number of groups are pursuing diamond CRL fabrication [2, 3]. Euclid Techlabs fabricated a two dimensional diamond lens and had a successful focusing measurement done at the Advanced Photon Source [4]. We developed an in-house fs-laser micromachining facility along with the post-ablation polishing procedure [5]. In this paper we report on status of diamond lens development.

DIAMOND LENS MANUFACTURING

Using machinery developed in-house in the past year we produced a new set of diamond lenses. Figure 1 shows a typical lens geometry along with polishing bit and a microscope image of the laser cut lens.

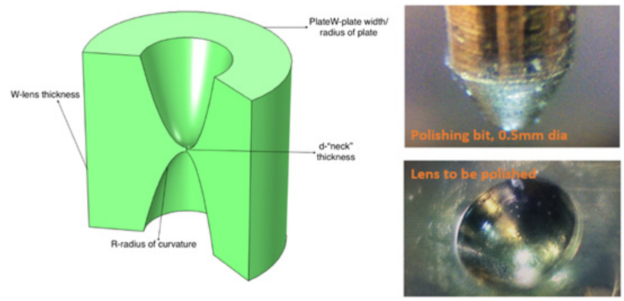

Figure 1: Left: Refractive lens geometry. Right: Top: polishing bit. Bottom: lens ablated in a diamond plate.

DIAMOND LENS METROLOGY

Visible light metrology (white light profilometry, confocal scanning microscopy, and others) did not give consistent results primarily due to the transparency of diamond samples and parabolic shape of the surface (these methods rely on light coming back to the sensor). Also, these methods do not probe potential structural features inside the optical element that are sampled by x-rays. X-ray metrology at the design operational energy is the best way to characterize an optics system. There are several methods that could be used, including ptychography and Talbot grating interferometry.

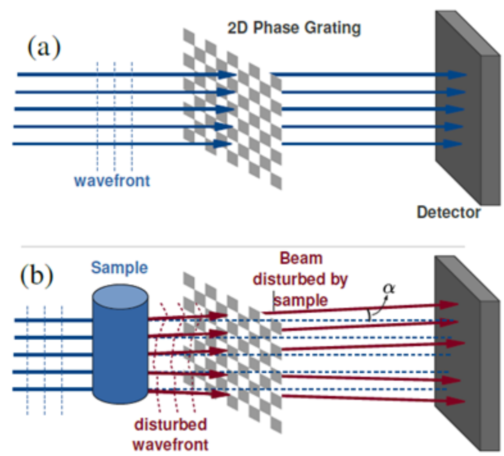

Figure 2: Schematics of a single-grating interferometry setup, showing the wavefront propagating through a checkerboard grating (a) without and (b) with the distortion from a sample (from [6]).

Single-grating interferometry [7] relies on the Talbot self-imaging effect [8], which results in a series of sharp images formed along the beam path, when light is transmitted through the periodic structure of the grating. These self-images are formed at specific distances downstream from the grating [9], the so-called Talbot

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distances, which are determined by the grating period, the photon wavelength, and the grating pattern (e.g., meshed or checkerboard gratings).

The visibility (contrast) of the interferogram is affected by the coherence of the incoming beam [10]. Depending on the degree of coherence, the contrast of the self-image can deteriorate very rapidly, thereby limiting the maximum distance at which the Talbot images can be formed. However, even with a moderately coherent beam, it is possible to observe Talbot images at short distances by using a grating with a small period.

A basic experiment using the grating interferometry consists of measuring and using the deformation of the Talbot image to retrieve the wavefront. The Talbot images are deformed by the shape and features of the wavefront transmitted by the test object (see Fig. 2).

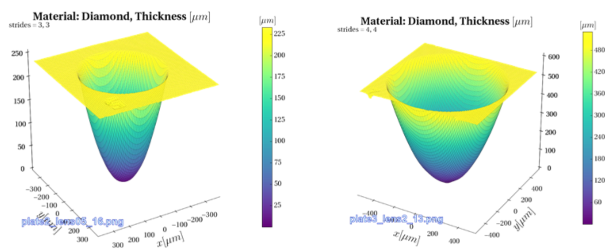

Figure 3: Grating interferometry results: lens profiles. Left: 450um aperture, 250um deep lens. Right: 800um aperture, 500um deep lens.

The procedure to retrieve the wavefront is described in [7]. Single-grating Talbot imaging for wavefront sensing and x-ray metrology is utilized at the Argonne Advanced Photon Source [7] for in-situ metrology. By giving up transverse spatial resolution, one gains in the data acquisition and analysis speed. Data acquisition times of ~ 10 seconds were demonstrated for compound refractive lenses.

Figure 3 shows the 3D density map of two lenses. Large aperture lens (Fig. 4) is quite parabolic, with standard deviation of the paraboloid fit residual well under 1 micron (circled on Fig. 4). The residual (Fig. 4, right) is random.

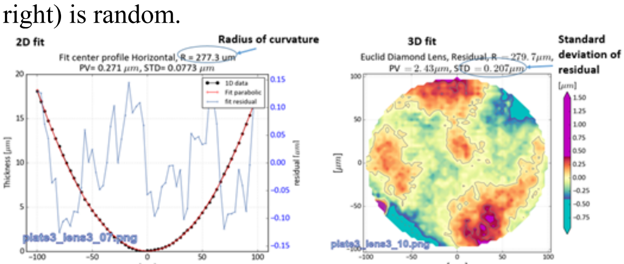

Figure 4: Grating interferometry results for an unpolished large radius of curvature lens on a small aperture (200 um). Left: 2D fit across horizontal line. Right: 3D fit residual.

Figure 5 shows measurement result of the double sided lens with equivalent radius of curvature of about 60 microns. The lens was polished and that is why residual is almost rotationally symmetric (Fig. 5, right). Also note, that residual (Fig. 5, left, blue curve) is highly correlated. This means that it can be corrected in manufacturing process or a correcting phase plate can be envisioned.

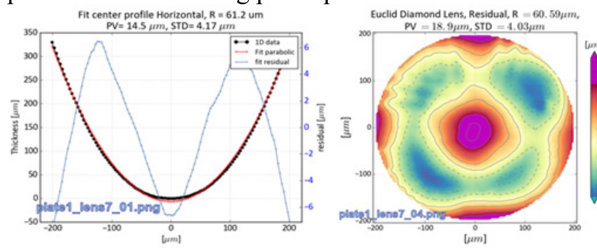

Figure 5: Grating interferometry results for a polished small radius of curvature lens on large aperture (400 um). Left: 2D fit across horizontal line. Right: 3D fit residual.

In upcoming months we will produce a new set of lenses taking into account the measurement results from the measurement run at the APS. We will correct the ablation procedure to include a corrective plate – inverse of the residual (Fig. 5, left, blue trace).

In parallel we are working on packaging diamonds into a holder fixture. We have diamond embedded into a 1” diameter stainless steel cylinder, similar to beryllium lens packaging.

ACKNOWLEDGEMENT

This project is supported by Small Business Innovative Research phase I grant DE-SC0013129.

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