SINGLE CRYSTAL DIAMOND X-RAY LENS DEVELOPMENT

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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 is the best material for high heat load applications. Moreover single crystal lens preserves coherence of the x-ray beam because scattering from grain boundaries, voids and impurities, typical for current beryllium lenses is minimized. We report the fabrication and performance evaluation of single crystal diamond refractive x-ray lenses with a paraboloid of rotation form factor for focusing x-rays in two dimensions simultaneously. The lenses were manufactured using a femtosecond laser micromachining process and tested using x-ray synchrotron radiation at the Advanced Photon Source of Argonne National Laboratory. These lenses were stacked together to form a traditional compound refractive lens (CRL). Due to the superior physical properties of the material, diamond CRLs are enabling and indispensable wavefront-preserving primary focusing optics for x-ray free-electron lasers and the next-generation synchrotron storage rings. They can be used for highly efficient refocusing of the extremely bright x-ray sources on secondary optical schemes with limited aperture such as nanofocusing Fresnel zone plates and multilayer Laue lenses.

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]

It is however a challenging task to manufacture complex shapes out of diamond. In this proposal we use femtosecond laser cutting technology to manufacture a compound refractive lens (CRL), the most popular x-ray optics element, made out of a single crystal diamond. A femtosecond laser pulse duration is extremely short: material is ablated while pulse heating effects are minimized.

DIAMOND LENS MANUFACTURING

The lenses presented here were manufactured from a single crystal CVD 587-microns-thick diamond plate. To machine a 2D paraboloid, the fs-laser beam was steered by a galvo mirror to ablate circle patterns gradually reducing the circle diameter with depth. The largest diameter on the diamond surface was of about 450 μm (Figure 1).

By combining objectives of different magnification and enhanced contrast imaging, interference fringe diameters at different vertical positions of the focal plane, with the diamond surface set to zero as a reference, were recorded. All fringes (representing 2D cross-sections of a 3D solid at every focal plane parallel to the surface) were quasi-circular confirming that the micro-machined lenses were paraboloids.

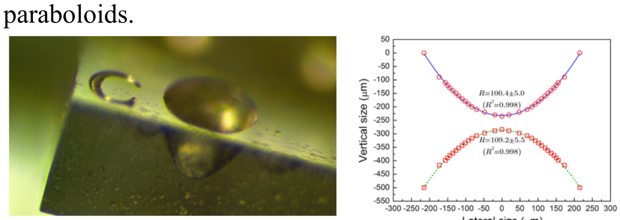

Figure 1: Left: Microscope image of the lens. Right: Profile of the lens measured by an optical profilometer and parabolic fit with radii of curvature.

The diamond lens polishing was attempted using a custom – made tool that will spin the diamond slurry inside of the lens (Figure 2). We used CNC machine-based setup with integrated video-microscope. We started with 0.25μm slurry and later used 0.1μm to obtain the required 0.1μm surface finish. A special tool was used to spin diamond slurry inside the lens cavity. We are working to further improve polishing process.

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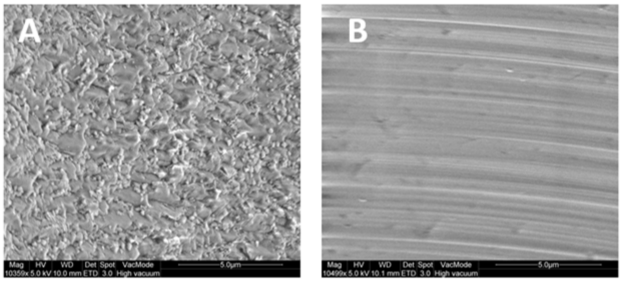

Figure 2: Scanning electron microscope image, same scale (5 μm). A – after laser cutting, B – after polishing.

X-RAY BEAM FOCUSING WITH DIAMOND CRL

We assembled a CRL prototype by stacking together three diamond lenses [4]. The total device length was 1.5 mm with the focal length of 3.36 meters at 11.85 keV x-ray energy and a total aperture of 450 μm. This CRL was tested using undulator radiation at the Biophysics Collaborative Access Team at the APS [5]. It was installed at 62 meters from the source. A circular pinhole aperture with a diameter ~ 400 μm was placed in front of the CRL. An ideal CRL would refocus the nearly Gaussian undulator source with a size of 652 x 27 μm^2 to an image with a size 37.3 x 1.55 μm^2 FWHM [6]. The focused beam profile measured with the CCD at 3.55 m from the lens was 52.6 x 21.4 μm^2 (Figure 3). This discrepancy comes from an individual lens shape deviation from an ideal paraboloid profile and surface roughness combined with stacking error. This result gives an indirect measure of effects coming from the shape deviation. The horizontal size of the beam is significantly larger than the vertical size and therefore is much less sensitive to CRL stacking misalignments.

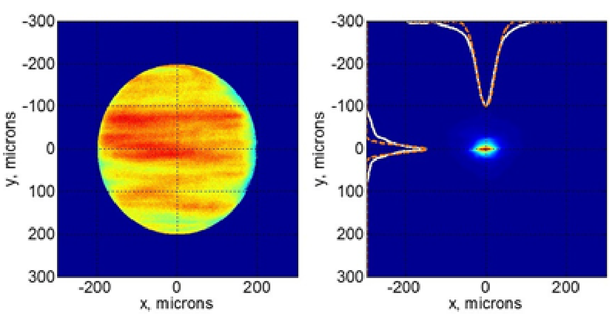

Figure 3: Left (lens out): Image of the aperture limited beam. Right (lens in): Image of the 11.85 keV x-ray beam focused by the CRL. Beam projections on x and y axes (white, solid), Gaussian fit (orange, dashed). The focused beam size is 52.6 x 21.4 μm^2.

The transmission through the CRL was 74%. The focused beam deviates from the Gaussian due to imperfections of lens geometry, limited stacking precision and the surface roughness. However the Gaussian portion of the beam is 71%. To calculate the gain of the lens we corrected the experimental transmission value to include only the Gaussian portion. The effective transmission of the CRL was 0.53 and the corresponding gain was 53.5.

HEAT LOAD SIMULATIONS

We used finite element analysis (ANSYS, [7] and COMSOL, [8]) to estimate the temperature rise of the lens under the thermal load coming from x-ray absorption in the lens. Beryllium absorbs much less of the incident x-ray energy. For a 1 kW, 12 keV x-ray, the diamond lens absorbs 79 W and an identical geometry *beryllium lens absorbs 6.5 times less power*, - only 12 W. However the thermal properties of diamond allow it to cool efficiently and its maximum temperature rise is smaller (Figure 4).

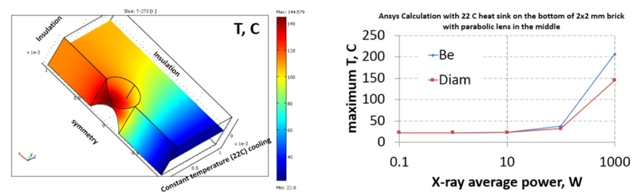

Figure 4: High power X-band multipactor ignition switch experiment layout.

The thermal expansion coefficient *α* of the diamond is *10.5* times smaller than of beryllium. The refractive decrement, δ of the diamond is 2.15 times larger than of beryllium. Thermal expansion leads to the change in the focal distance of the lens $\Delta F = \alpha \cdot R \cdot \Delta T / 2\delta$. Therefore the change of the focal length for the beryllium lens is 23 times larger for the same temperature rise ΔT! This means that diamond lenses should be capable of operating at significantly higher temperatures (hence much higher heat loads) than beryllium ones.

ACKNOWLEDGEMENT

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