Figure Metrology for X-Ray Focusing Mirrors with Fresnel Holograms and Photon Sieves

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Abstract: We report on interferometric measurements of the figure error of an ultra-precise mirror with the shape of an elliptical toroid for the diffraction limited focusing of hard x-rays from an undulator x-ray source. We describe measurement configurations using Fresnel type holograms and photon sieves, and evaluate the measurement uncertainty.

OCIS codes: 050.1970, 220.1250, 220.4840, 340.7430

1. Introduction

Synchrotron and free-electron laser x-ray sources with high brilliance and low emittance have become indispensable tools for research in material science, geophysical science, environmental science, and life science. Micro- and nano-focused x-ray beams are essential characterization tools for many applications in these areas, where high flux combined with high resolution is of paramount importance. These properties can be achieved by a variety of means, including capillary optics, crystal focusing, waveguides, Kirkpatrick-Baez (K-B) mirrors, zone plates, compound refractive optics, and, more recently, multilayer Laue lenses. Focusing x-ray K-B mirrors have the advantages of being achromatic and highly efficient. All x-rays of all wavelengths at brought to a single focus with over 90% reflectivity. X-rays undergo total external reflection at very low grazing angles below a critical angle θ_c, because the index of refraction of mirror materials is less than unity. In the hard x-ray regime the angle is typically a few mrad, depending on the reflecting material. Diffraction limitied focusing requires that x-ray mirrors are shaped to an elliptical figure with sub-nanometer figure error and with an allowable surface slope error of the order of 10 nrad. The very stringent specifications for current and future x-ray mirror optics, combined with the free-form mirror shape, are a challenge that requires the continued development of specific metrology for x-ray optics with very low measurement uncertainty. We describe and evaluate interferometric measurement methods for free-form x-ray mirrors based on computer generated holograms that generate precise test wavefronts for x-ray mirrors.

2. Elliptical Mirror Description

Elliptical mirrors for the focusing of x-rays from synchrotron radiation sources can be characterized by their focusing properties as is shown in Fig. 1. X-rays emitted by a source located at a point F_1 impinge at a grazing angle θ on an elliptical mirror at a distance S_1 from the source, and are brought to a focus F_2 at a distance S_2 from the mirror center. The grazing angle θ on the mirror must be smaller than the critical angle θ_c for x-rays to be reflected. For the x-ray mirror shown in Fig. 2, the grazing angle is 3 mrad (0.172 °). For x-ray applications that require high spatial resolution it is critical that the beam is brought to a very tight focus; the x-ray mirror must strongly demagnify the light source. The mirror shown in Fig. 2 was designed for a distance S_1 from the source to the center of the mirror of 60 m. The distance from the center of the mirror to the focus of the x-ray beam is only 60 mm, resulting in demagnification of the light source by a factor S_1/S_2 = 1000 due to the conservation of etendue.

The functional parametrization of an elliptical mirror with the parameters S_1, S_2, and θ is not well suited for characterizing the shape of the mirror with optical metrology, because these parameters cannot be measured easily and accurately with optical metrology tools. The more familiar parametrization of an ellipse by its major and minor semi-axes a and b can be calculated from the parameters S_1, S_2, and θ as follows:

$$a = \frac{1}{2}(S_1 + S_2) \quad \text{and} \quad b = \sqrt{a^2 - c^2}\,, \quad \text{where} \quad c = \sqrt{\frac{tan^2\theta\,(S_1 - S_2)^2 + (S_1 + S_2)^2}{2\sqrt{tan^2\theta + 1}}}\,. \tag{1}$$

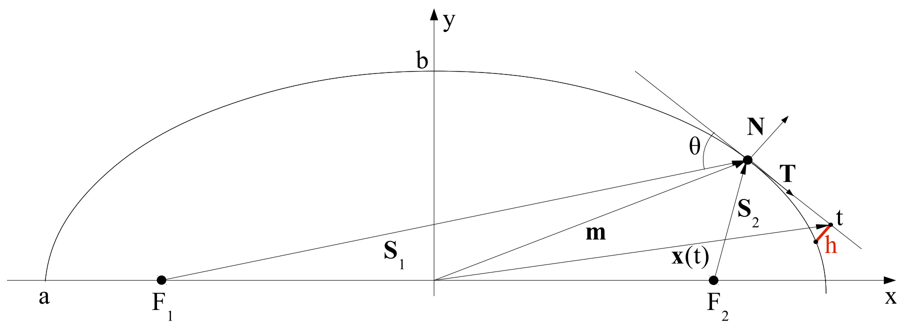

Fig. 1. Parameters characterizing an elliptical mirror with the center located at **m**.

The vector

$$\mathbf{m} = \begin{pmatrix} x_m \\ y_m \end{pmatrix} = \begin{pmatrix} (S_1^2 - S_2^2)/4c \\ b\sqrt{1 - \left[(S_1^2 - S_2^2)/4ac\right]^2} \end{pmatrix} \tag{2}$$

denotes the position of the mirror center in the coordinate system of the ellipse as shown in Fig. 1. For the mirror in Fig. 2 with S_1 = 60 m, S_2 = 60 mm, and θ=3 mrad, the major and minor semi-axes are a = 30030 mm and b = 5.6921 mm. The mirror center position **m**, calculated with Eq. 2, is (29970 mm, 0.36 mm). Measurements of the mirror shape with interferometers [1, 2] or profilers [2, 3] generally produce mirror profile data $h(t)$ (shown in red in Fig. 1) in the coordinate system defined by the unit tangent vector **T** at **m**. In this part-centered coordinate system the profile $h(t)$ can be calculated for the points:

$$\mathbf{x}(t) = \mathbf{m} + t \cdot \mathbf{T} \tag{3}$$

on the tangent at **m** using the unit tangent and normal vectors **T** and **N** at the mirror center **m**:

$$\mathbf{T} = \begin{pmatrix} \sin\alpha_m \\ \cos\alpha_m \end{pmatrix} \quad \text{and} \quad \mathbf{N} = \begin{pmatrix} -\cos\alpha_m \\ \sin\alpha_m \end{pmatrix}, \quad \text{where} \quad \tan\alpha_m = -\frac{b^2}{a^2}\frac{x_m}{y_m}. \tag{4}$$

The resulting expression for the elliptical profile $h(t)$ is:

$$h(t) = \frac{1}{\hat{\mathbf{N}} \cdot \hat{\mathbf{N}}} \left(\hat{\mathbf{x}}(t) \cdot \hat{\mathbf{N}} - \sqrt{\left[\hat{\mathbf{x}}(t) \cdot \hat{\mathbf{N}}\right]^2 - \hat{\mathbf{N}} \cdot \hat{\mathbf{N}} \left[\hat{\mathbf{x}}(t) \cdot \hat{\mathbf{x}}(t) - a^2 b^2\right]} \right) \tag{5}$$

where

$$\hat{\mathbf{x}}(t) = \begin{pmatrix} b\,x(t) \\ a\,y(t) \end{pmatrix} \quad \text{and} \quad \hat{\mathbf{N}} = \begin{pmatrix} b\,N_x \\ a\,N_y \end{pmatrix}. \tag{6}$$

Kirkpatrick-Baez (K-B) mirrors are usually elliptical cylinders that are used in pairs to focus an x-ray beam in horizontal (tangential) and vertical (sagittal) directions. The mirror shown in Fig. 2 is part of a K-B mirror pair. It is made from a spherical substrate with about 40 m radius. Its surface is polished to an elliptical figure along the long (tangential) direction. The incident beam, which about 100 microns wide, is brought to a focus in tangential direction. The mirror does not focus in the sagittal direction.

3. Testing with Fresnel Holograms and Photon Sieves

The mirror shown in Fig. 2 can, in principle, be measured against an interferometer reference flat if the interferometer has sufficient dynamic range. However, the high fringe density will cause a measurement error due to the non-common path, which is difficult to quantify. Alternatively, a binary diffractive optical element, which is fabricated with a precise lithography process, can be used to generate a test wavefront that matches the shape of the x-ray mirror. The interferometer is then used at near zero fringe density at which its measurement uncertainty is lowest.

We evaluate a measurement setup that uses a Fizeau interferometer with a collimated test beam and a reference flat. The hologram faces the x-ray mirror which is positioned at a distance of 50 mm from the hologram. The x-ray mirror is rotated by an angle of 5 °about the vertical axis of the hologram, which increases the diffraction angles and enables

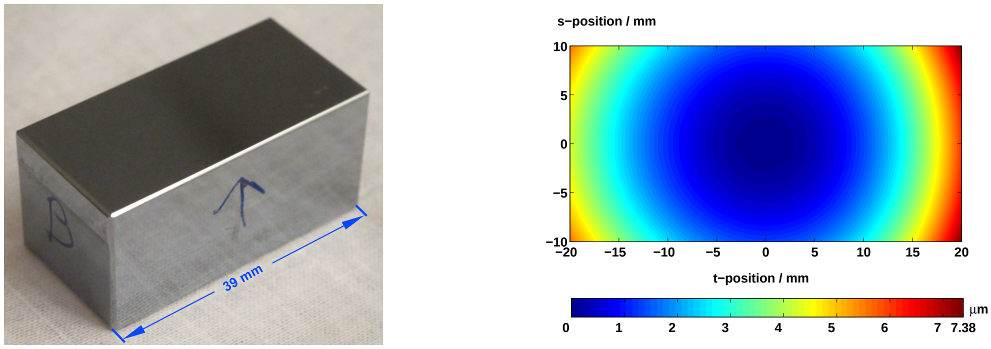

Fig. 2. X-ray mirror made from a silicon crystal for focusing an x-ray beam emitted by an undulator at the Advanced Photon Source (APS). The mirror surface is an elliptical toroid with a maximum deviation from the tangent plane at the mirror center of about 7 μm. The shape of the mirror surface is shown on the right.

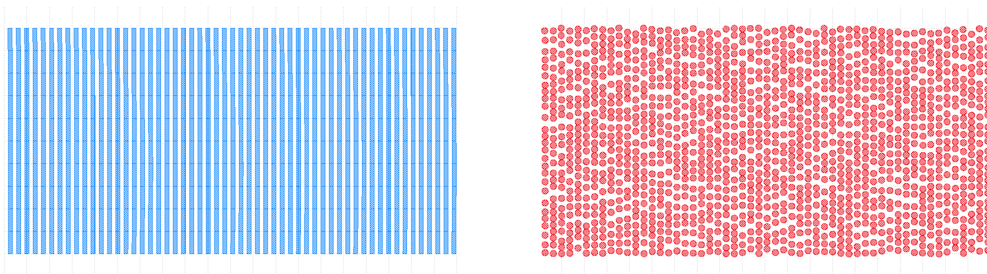

Fig. 3. Layouts of holograms for measuring the shape of the mirror shown in Fig. 2. For illustration purposes, the holograms shown here were calculated for 100× the interferometer wavelength of 632.82 nm. A Fresnel type hologram is shown on the left, the equivalent photon sieve on the right. The actual Fresnel zone width is approximately 3.5 μm.

separation of diffraction orders. The Fresnel hologram for this measurement configuration is shown on the left side of Fig. 3. Photon sieves [4] are an alternative type of hologram that effectively suppress higher diffration orders, which reduces coherent noise and lowers the measurement uncertainty for interferometric measurements of x-ray mirrors. A photon sieve for measuring the mirror in Fig. 2 is shown in Fig. 3 on the right.

The work done at the APS was supported by the U.S. Department of Energy, Office of Science, under Contract No. DE-AC02-06CH11357.

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