Sub-nanometer Interferometry for Aspheric Mirror Fabrication

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ABSTRACT

Aspheric mirrors for extreme ultraviolet lithography (EUVL) at a wavelength of 13nm require surface figure accuracy approaching 0.10nm rms. A new type of interferometry, based on the fundamental process of diffraction, is described that has the intrinsically ability to achieve this accuracy on aspherical surfaces. However, care must be taken in the design and implementation of the optical system that images the aspheric mirror onto the CCD camera. Non-common paths of the measurement and reference wavefronts within the optical system, as well as distortion of the image of aspheric mirror on the CCD, must be addressed in order to realize sub-nanometer accuracy.

The phase shifting diffraction interferometer and the mitigation of potential imaging errors are described for measuring the surface figure on aspheric mirrors.

Keywords: Aspheric metrology, interferometry, error mitigation.

1. INTRODUCTION

The projection optics for EUVL are based on all reflective ring-field imaging systems made up of three or more off-axis multilayer coated aspheric mirrors. If these projection systems are to achieve diffraction limited performance over the full depth of focus, the deviation of the wavefront from spherical in the exit pupil must be better than $\lambda/14$ rms where λ=13nm is the operating wavelength. The wavefront error must therefore be less than 1.0nm rms. If the imaging system is made up of four mirrors, the error contribution from each mirror can be no larger than 0.50nm rms (assuming uncorrelated errors), or 0.25nm rms surface figure error (due to the doubling of the error on reflection). For more advanced designs using additional mirrors, the permissible surface error is even smaller.

Fabrication of these mirrors requires real-time metrology to serve as the feedback mechanism for the finishing process. Visible light (λ_v) interferometry is the metrology of choice during optical fabrication because there is sufficient reflectivity at visible wavelengths (the reflectivity of the glass surface is essentially zero at λ=13nm) to measure the surface figure.

To achieve the required measurement accuracy on aspheric mirrors, the phase shifting diffraction interferometer was developed. It is based on simplifying interferometry - minimizing the number of critical components and eliminating those parts that limit accuracy, including the reference surface and most of the auxiliary optics.

2. INTERFEROMETER

The phase shifting diffraction interferometer[1] (PSDI) described here is based on diffraction. Diffraction is a fundamental process that permits the generation of near-perfect spherical wavefronts over a specific numerical aperture by using a circular

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aperture with a radius comparable to the wavelength of light. Over a finite numerical aperture this wavefront can be arbitrarily good. For example, if the aperture has a radius of $3\lambda_v$ then the deviation of the diffracted wavefront from spherical is less than $\lambda_v/10^6$ over a numerical aperture (NA) of 0.2 in the far field of the aperture. Using this principle, two independent wavefronts can be generated - one serves as the measurement wavefront and is incident on the optic or optical system under test and the other serves as the reference wavefront. Since they are generated independently their relative amplitudes and phases can be controlled, providing contrast adjustment and phase shifting capability. This concept can be implemented in several different ways. The one described here is based on single mode optical fibers that provide the diffracted wavefronts.

Fig. 1 shows the PSDI configured for measuring the surface figure of a concave off-axis aspheric mirror. The light source is a short coherence length laser operating at λ_v =532nm. The output beam is divided into two equal intensity beams by a polarization beamsplitter. One beam is reflected from a retroreflector mounted on a piezoelectric phase shifter[2] and the other beam is reflected from a retroreflector mounted on a variable delay line. The two beams are recombined by the polarization beamsplitter and launched into a single mode optical fiber. The end of the fiber is placed on the optical axis of the mirror at an axial position to minimize the aspheric

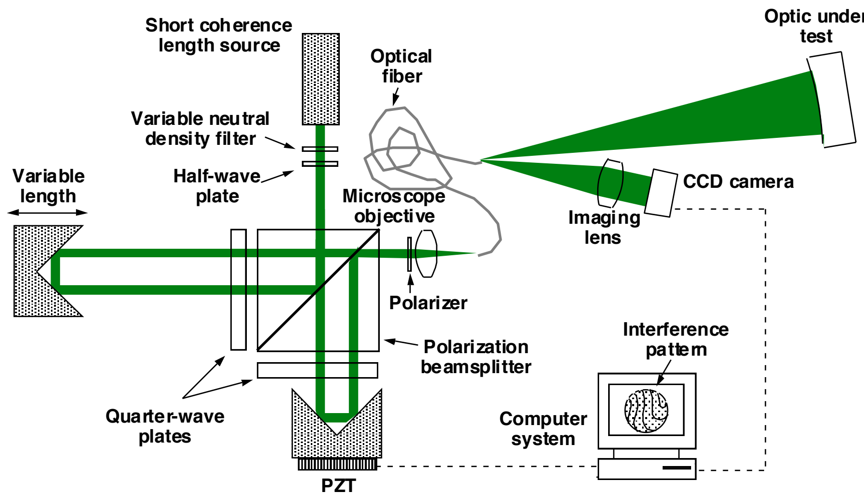


Fig. 1. PSDI configured to measure the surface figure of a concave off-axis aspheric mirror.

departure over the clear aperture of the mirror. The delay path-length is set equal to the round-trip distance from the fiber to the mirror. The spherical wavefronts diffracted from the end of the fiber have sufficient numerical aperture to illuminate both the mirror and imaging lens. The phase-shifted wavefront reflected from the mirror is focused back onto the fiber as shown in Fig. 2. It is reflected from the semi-transparent metallic coating on the end of the fiber, combining with the delayed diffracted wavefront. Since the optical path difference between these wavefronts is identically zero, the wavefronts are temporally coherent and interfere. Extraneous wavefronts from the interferometer are temporally incoherent and do not interfere with the primary wavefronts. They do however produce a background and reduce the fringe visibility of the interfering wavefronts.

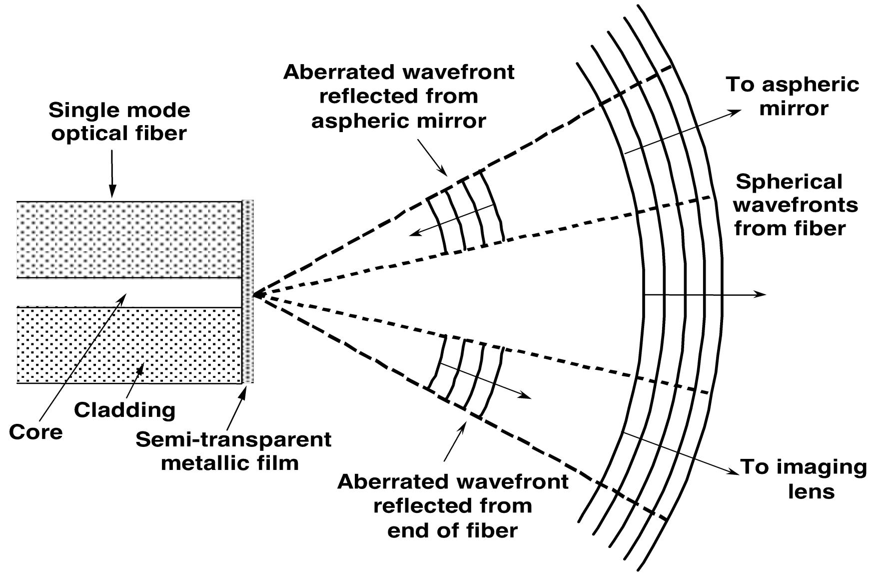
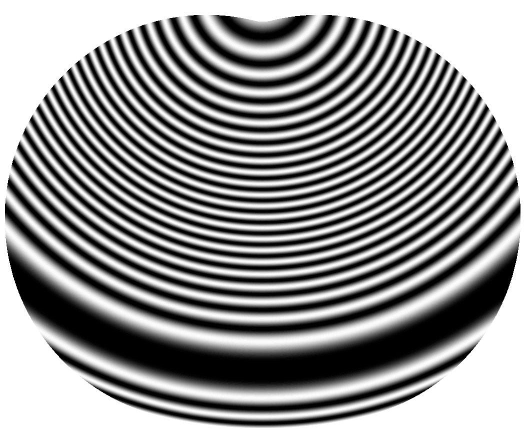
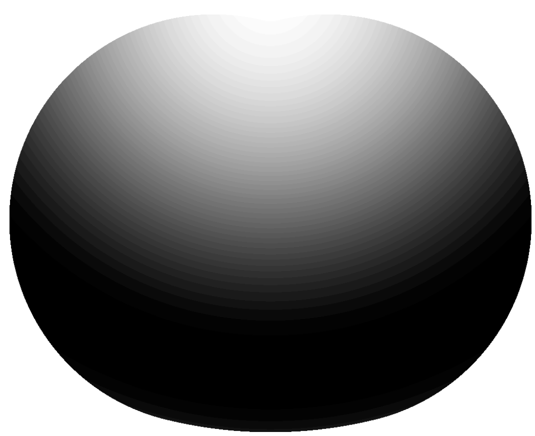


Fig. 2. Detail of the diffracted and reflected wavefronts at the end of the fiber.

Interference is observed in the image plane of the aspheric mirror with a CCD camera. Fig. 3a shows the interference pattern of an off-axis aspheric EUVL mirror (designated M4) where the null fringe is positioned to minimize fringe density (not necessarily the best fit sphere). The phase is determined using phase shifting techniques and phase extraction algorithms[3] and is shown in Fig. 3b. The aspheric departure of this particular mirror is approximately 6μm. The figure error in the mirror is found by subtracting the measured departure from the theoretical aspheric equation that defines the perfect mirror.



(a)



(b)

Fig. 3. (a) Interferogram of a concave off-axis aspheric EUVL mirror M4. (b) The calculated phase. The aspheric departure is approximately 6μm.

In principle this is straightforward. However, an imperfect imaging system can introduce subtle errors when measuring an asphere that are not present when measuring a spherical surface. These errors will severely limit the absolute accuracy of the measurement unless care is taken to understand and minimize them.

3. ERROR SOURCES UNIQUE TO ASPHERES

Measuring aspheric mirrors is quite different from measuring spherical mirrors. The imaging system becomes a critical part of the interferometer for two reasons: the measurement and reference wavefronts do not travel the same optical paths through the imaging system; and distortion results in a mapping error between the mirror coordinate system and the CCD coordinate system.

3.1. WAVEFRONT SHEAR

The imaging system for the PSDI is specifically designed for the particular aspheric mirror to be tested. A typical system is shown in Fig. 4. The paths of the measurement and reference wavefronts are shown for an arbitrary ray pair that interfere at the CCD. Note that the measurement wavefront reflects from the fiber and the fold mirror and passes through the imaging lens at different spatial positions

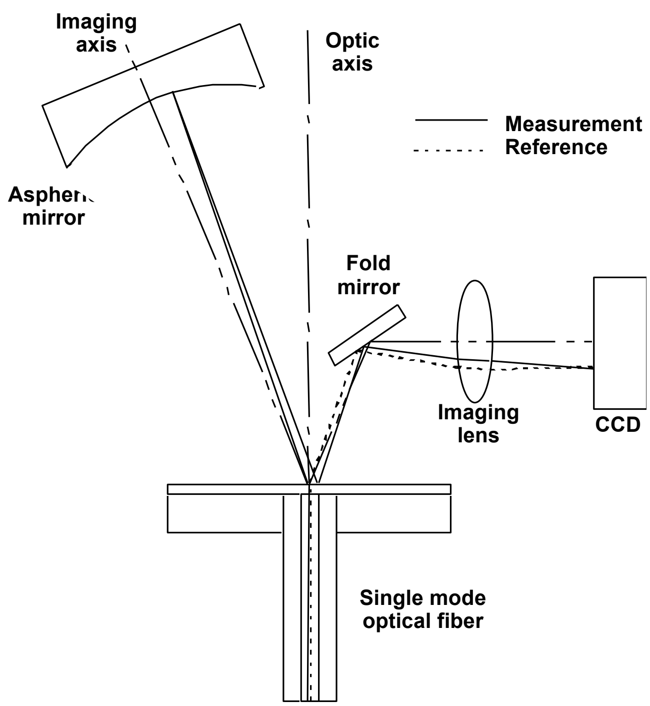
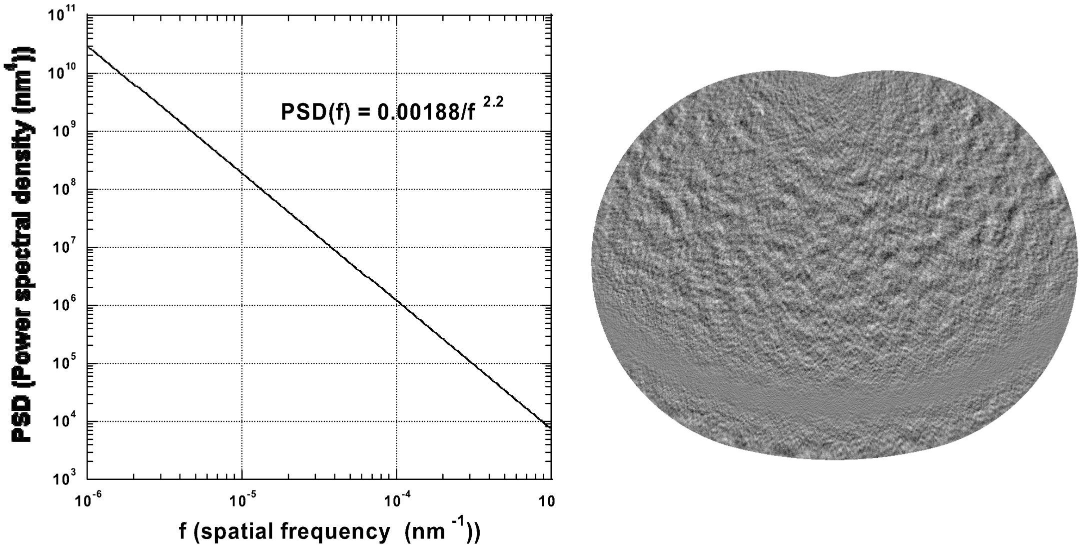


Fig. 4. The imaging system (not to scale) for the PSDI consists of the surface of the optical fiber, the fold mirror, the imaging lens and the CCD. Measurement and reference wavefronts do not travel identical paths through the imaging system when measuring aspheres.

than the reference wavefront. Wavefront shear at each component, although quite small, introduces slightly different optical path-lengths due to imperfections in the optics. These imperfections are usually the results of fabrication errors in figure and surface roughness. The imaging lens is specifically designed to be insensitive to differential shear but it can introduce path-length errors if not properly fabricated. For example, suppose each polished surface of the imaging lens has the power spectral density (PSD) shown in Fig. 5a, which is typical for commercial lenses. The corresponding surface roughness for each surface (over the spatial frequency range from 1.0mm^{-1} to 1.0μm^{-1}) is 0.84nm rms. For a three element (six surfaces) imaging lens the induced measurement error of mirror M4 is shown in Fig. 5b. The maximum shear in this specific case was 100μm. Note that the spatial character of the error is dependent on the fringe density. At the position of the null fringe (the broad fringe in Fig. 3a) the error is zero. The induced figure error (spatial frequencies <1.0mm^{-1}) over the entire aspheric surface is 0.21nm rms.



(a) **(b)**

Fig. 5. (a) The power spectral density for the surface finish (0.84nm rms) of a typical lens over the spatial frequency range 1.0mm^{-1} to 1.0μm^{-1}. (b) The induced error (0.21nm rms) in the measurement of the aspheric mirror M4.

The same type of error can be introduced at any optical element where the measurement and reference wavefronts are sheared. It is therefore very important to: (1) minimize the number of optical components in the interferometer; (2) model, specify and test all components that go into the interferometer to be certain that they do not limit the desired accuracy of the interferometer and; use tilt and rotational averaging to statistically reduce residual random errors.

3.2. DISTORTION

The imaging system for the PSDI has three coordinate systems associated with it. The equation that defines the aspheric shape of the mirror surface is in the parent mirror coordinate system, perpendicular to the optic axis and centered at the virtual vertex of the aspheric mirror. The off-axis segment of the aspheric mirror is in the local mirror coordinate system, perpendicular to the imaging axis and centered where the axis intersects the mirror. The CCD array coordinate system is perpendicular to the imaging axis and centered where the axis intersects the CCD (the image plane). Proper mapping from CCD coordinates to local mirror coordinates to parent mirror coordinates is critical. Mapping errors due to geometric uncertainties, incorrect magnification and distortion translate directly to aspheric measurement errors.

CCD distortion (unequal pixel spacing) is characterized by illuminating the CCD with two phase-shifted spherical wavefronts from optical fibers. From analysis of the interference pattern, pixel position distortion can be characterized.

The PSDI imaging systems are designed for minimum distortion. Distortion, however, is always present at some level due to residual distortion in the lens design or fabrication of the imaging lens. It is therefore necessary to measure the distortion directly. This is done with a calibration grid of fiducials deposited on a surrogate mirror with the same radius of curvature as the aspheric mirror. The positions of the fiducials are found in local mirror coordinates with a coordinate measuring machine. The surrogate is then placed in the interferometer and the positions of the images of the fiducials are found in CCD coordinates. A mapping between the two coordinate systems is generated and stored in the analysis software to assign CCD phase measurements to the correct mirror surface location. This mapping is checked periodically to account for any long-term drifts of the interferometer.

Distortion must be eliminated or compensated, no matter where it originates, or the wrong aspheric figure will be polished into the mirror during fabrication. Fig. 6 shows a 0.60nm rms figure error that would be polished into mirror M4 for 0.1% cubic distortion.

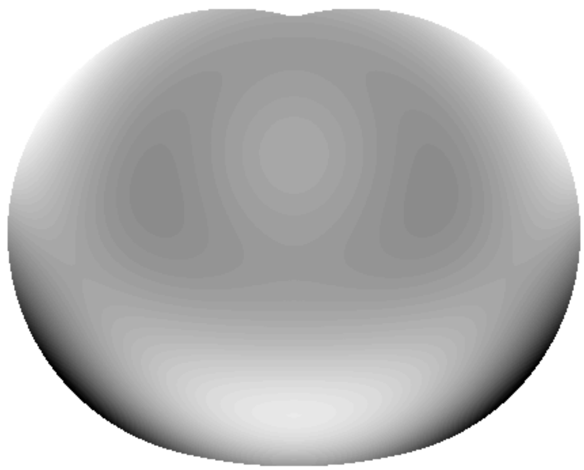
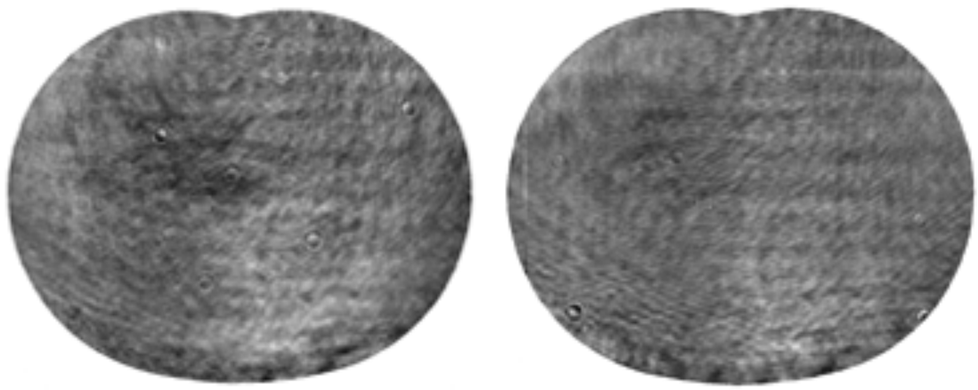


Fig. 6. Error polished into the aspheric mirror M4 when there is uncompensated 0.1% cubic distortion at the edge. Error is 0.60nm rms.

4. ASPHERIC MEASUREMENTS

Several aspheric mirrors have been fabricated using PSDIs as the feedback metrology. PSDIs have been installed at the vendor's facility to minimize the time between polishing and interferometry. PSDIs are used at Lawrence Livermore National Laboratory to certify the completed aspheric mirrors. Two independent measurements of aspheric mirror M4 are shown in Fig. 7. The small difference in the measurements, both quantitative and qualitative, is attributed to residual systematic errors.

At present it is estimated that the absolute accuracy of the PSDI is about 0.25nm rms. Further work is underway to achieve 0.10nm rms accuracy which will be required for future production EUVL projection systems.



(a) (b)

Fig. 7. Measurements of aspheric mirror M4 showing the deviation from the theoretical equation that defines the perfect surface figure. (a) LLNL (0.55nm rms); (b) vendor (0.44nm rms).

5. SUMMARY

An interferometer has been developed that intrinsically has the sub-nanometer accuracy necessary to measure aspheric EUVL mirrors. Aspheric measurements, in general, put much higher demands on the interferometer's imaging system than do spherical measurements. A flawed imaging system can introduce subtle errors that may go undetected until the aspheric mirrors are assembled in a projection system. The sources of these errors have been addressed and inter-comparison of measurements gives an estimated accuracy of 0.25nm rms. Development of higher accuracy PSDIs is underway.

ACKNOWLEDGMENTS

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