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Phase Shifting Diffraction Interferometry for Measuring Extreme Ultraviolet Optics

G. E. Sommargren

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Gary E. Sommargren
Lawrence Livermore National Laboratory, University of California, Livermore, CA 94550

Abstract

Extreme ultraviolet projection lithography operating at a wavelength of 13nm requires surface figure accuracy on each mirror to be better than 0.25nm rms. A new type of interferometry, based on the fundamental process of diffraction, is described that can intrinsically achieve the required accuracy. Applying this principle, two independent spherical wavefronts are 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 amplitude and phase can be controlled, providing contrast adjustment and phase shifting capability. Using diffraction from a single mode optical fiber, different interferometers can be configured to measure individual mirrors or entire imaging systems. Measurement of an EUV projection system is described.

Key words: Microlithography, metrology, interferometry.

Introduction

Extreme ultraviolet projection lithography operating at a wavelength of 13nm is based on all reflective imaging systems made up of three to five multilayer coated mirrors. If these imaging systems are to achieve diffraction limited performance, the deviation of the wavefront from spherical in the exit pupil must satisfy the Maréchal condition of $\lambda/14$ rms where λ 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 0.5nm rms (assuming uncorrelated errors), or 0.25nm rms surface figure error (due to the doubling of the error on reflection).

Fabrication of these mirrors requires real-time metrology to serve as the feedback mechanism for the finishing process. Visible light interferometry is the metrology of choice for optical fabrication for several reasons: the unit of measure is the wavelength of light which is stable and traceable and can be further subdivided to give increased resolution; the surface of the optic under test can be spatially sampled at many points ($>10^5$) simultaneously; and the data acquisition time is typically less than one second. For the characterization of most optics, where $\lambda/20$ to $\lambda/50$ rms accuracy is sufficient, commercial interferometers are adequate. However for EUV optics this is not the case. For a typical testing wavelength of 633nm, $\lambda/50$ corresponds to about 12.5nm, a factor of 50 larger than the accuracy required for EUV mirrors.

The accuracy of surface figure interferometers is limited by several factors, the two most important being the quality of the reference (whether an optical surface, null lens or computer generated hologram) and the quality of the auxiliary optics. Since interferometry is a comparative technique the accuracy of the reference directly affects the accuracy of the measurement of the optic under test. This is the primary source of error in an interferometer. Although several methods have been developed to increase the accuracy by making a series of measurements with the reference in transposed positions, the accuracy needed for EUV optics has not been demonstrated.

A secondary source of error involves the auxiliary optics outside the interferometer cavity that define the wavefront incident on the interferometer. This wavefront typically deviates from a plane or sphere by a significant fraction of a wavelength. The effect it has on a measurement is usually dismissed using "common path" arguments. To first order this is true, however an imperfect incident wavefront produces a local shear between the measurement and reference wavefronts. The resulting measurement error cannot be ignored when qualifying EUV optics.

In general, if one looks at the development of surface figure interferometry over the last twenty years or so, great strides have been made in data acquisition and phase measurement with the advent of CCD cameras and N-frame phase algorithms. Little, however, has been done to eliminate the fundamental errors caused by the interferometer itself. One approach is to make the reference and auxiliary optics better, but this has diminishing returns. Another approach is to characterize the errors in the interferometer very accurately and subtract them from the measurement of the optic under test. This can work well for a specific optic under test but is quite tedious and must be repeated for each new optic.

The approach described in this paper is different. It is based on simplifying interferometry - minimizing the number of critical components and eliminating those parts that reduce accuracy, including the reference and auxiliary optics.

Interferometer

The interferometer described here is based on diffraction[1]. Diffraction is a fundamental process that permits the generation of near-perfect spherical wavefronts over a specific numerical aperture by using a circular aperture with a radius comparable to the wavelength of light. Fig. 1 shows the deviation of a diffracted wavefront from a true sphere. Over a finite numerical aperture this wavefront can be arbitrarily good. For example, if the aperture has a radius of 2λ then the deviation of the diffracted wavefront from spherical is less than λ/10,000 over a numerical aperture (NA) of 0.3 in the far field of the aperture. Using this principle, two independent wavefronts can be generated[2] - 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 amplitude and phase 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 which provide the diffracted wavefronts.

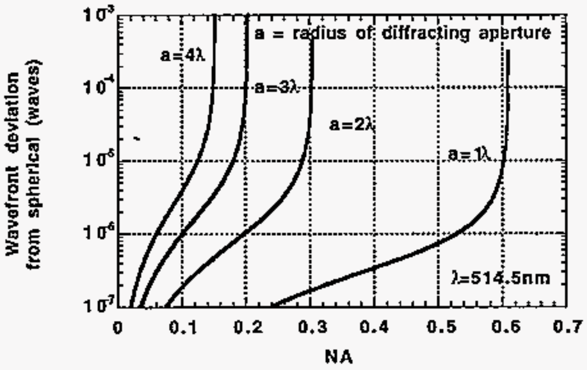


Figure 1. Plot of the deviation of a diffracted wavefront from spherical for different aperture radii **a**.

Fig. 2 shows the basic principle of operation. Light leaving the end of the single mode optical fiber diffracts to a spherical wavefront over an extended angular range. Part of this wavefront is incident on the optic under test and is reflected back toward the fiber. This aberrated wavefront reflects from a semi-transparent metallic film on the face of the fiber and interferes with part of the original spherical wavefront to produce the interference pattern. Fig. 3a shows the interferometer for testing optics where the end of the fiber is placed at a common conjugate. In this configuration two temporally incoherent beams are launched into the same fiber. One beam is first reflected from a retroreflector mounted to a piezoelectric phase shifter[3] and the other beam is delayed by a pathlength equal to the round-trip distance between the fiber face and the optic under test. Interference on the CCD camera takes place between the phase shifted wavefront that is reflected from the optic under test and the delayed wavefront diffracted directly from the fiber.

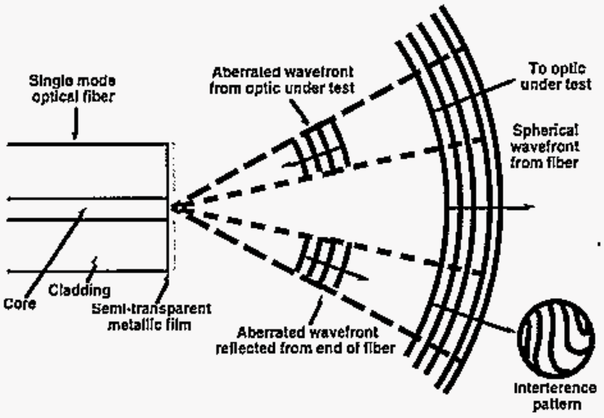
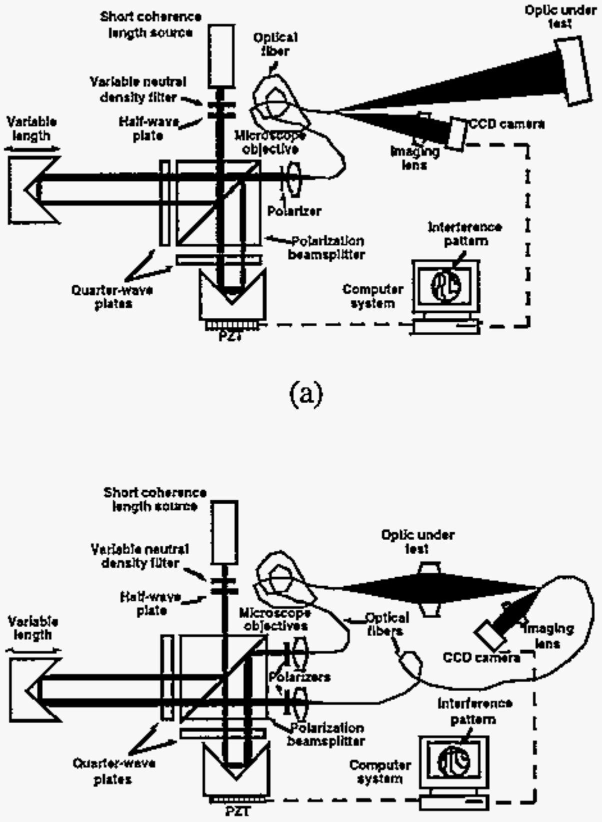


Figure 2. Principle of operation of the phase shifting diffraction interferometer using a single mode optical fiber (not to scale).

Fig. 3b shows the interferometer for testing optics where the ends of two fibers are placed at spatially separated conjugates. Here the two beams are launched into separate equal length fibers and the beam delay is equal to the pathlength between the fiber ends. Interference on the CCD camera takes place between the phase shifted wavefront from the first fiber that is transmitted through the optic under test and the delayed wavefront from the second fiber. In both configurations the optic under test is imaged onto the CCD camera.

Note that in each configuration the quality of the wavefronts before they are launched into the fibers is not important because the fibers act as spatial filters. Equally important is the fact that the measurement and reference wavefronts encounter no other optical components that can degrade accuracy before they interfere, except the end of the fiber which must have a flatness comparable to the desired accuracy of the measurement, but only over a very small area around the core of the fiber.



(a)

(b)

Figure 3. Two configurations of the phase shifting diffraction interferometer for measuring optics at: (a) a common conjugate; (b) distinct conjugates.

Testing

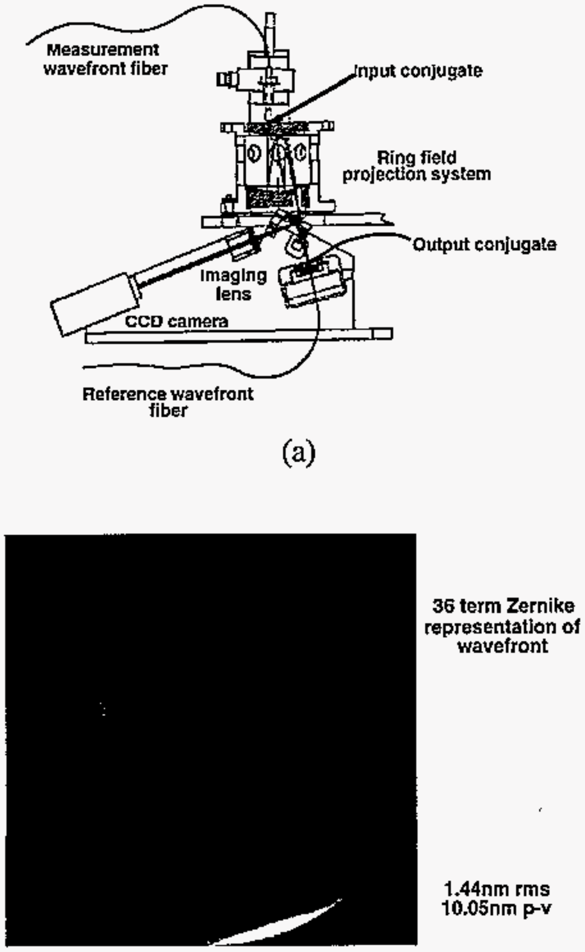
Self-consistency tests were run to determine the quality of the wavefronts from the fibers. In the first test two beams were launched into the same optical fiber. The two diffracted wavefronts interfered directly on the CCD camera. This test measures how precisely the wavefronts are matched. Theoretically the optical path difference should be zero over the full numerical aperture. Actual measurements showed the wavefronts are matched to better than 0.06nm rms. This test, however, does not demonstrate how spherical the wavefronts are.

This was determined with a second test where the interference between the wavefronts from two different fibers was measured for different angular shears. If the wavefronts are truly spherical the optical path difference should be the same over the full field, independent of angular shear. After subtracting the theoretical two point interference pattern from actual measurements, the wavefront difference was less than 0.30nm rms. The measurement accuracy appeared to limited not by the quality of the wavefronts but by the nonlinearity of the CCD and piezoelectric phase shifter, timing errors due to the phase-lock-loop on the digitizing board, and air turbulence and stratification within the measurement volume. The current accuracy of the interferometer is estimated to be better than 0.50nm rms

Several EUV optics have been measured including a projection system and an aspheric mirror. Of particular interest was an all spherical, two mirror, four reflection, ring field EUV projection system[4] designed by Lynn Seppala of Lawrence Livermore National Laboratory and fabricated by Tropel Corporation. The system has a numerical aperture of 0.06, giving a minimum feature size of 0.14μm and a depth of field of ±1.8μm over a ring field that is approximately 1.3x5.0mm². It is shown schematically in the interferometric setup in Fig. 4a. The simplicity of the measurement using optical fibers is apparent. The measured wavefront in the exit pupil, expressed as a 36 term Zernike fit (piston, tilt and power removed), is shown in Fig. 4b. The wavefront error is 1.44nm rms compared to the nominal design value of 0.42nm rms and the Maréchal condition of 0.93nm rms. This result is consistent with the resolution achieved in imaging experiments performed with test patterns on a reflective reticle.[5]

Summary

A new interferometer has been developed that intrinsically has the accuracy necessary to measure EUV optics, both individual mirrors and assembled projection systems. From initial tests of the interferometer the accuracy was estimated to be better than 0.50nm rms. EUV optics have been measured including a projection system and an aspheric mirror. Sources that limit the accuracy have been identified and work is now underway to minimize or eliminate them with the expectation of achieving an accuracy of 0.10nm rms.



(a)

(b)

Figure 4. Interferometric setup for measuring the EUV ring field projection system (a); measured wavefront in the exit pupil with piston, tilt and power removed (b).

Acknowledgments

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References and Notes

1. Parts of this paper were presented at the OSA Annual Meeting, Portland, OR (1995).
2. This differs from the point diffraction interferometer where the wavefronts are not independent. See, for example, R.N. Smartt and W.H. Steel, "Theory and application of point-diffraction interferometers," Japan. J. Appl. Phys. **14** (suppl. **14-1**), 351-356 (1975).
3. Phase shifting can also be accomplishment by axially translating either fiber, but the phase shift is not uniform across the spherical wavefront.
4. G.E. Sommargren, "Performance of a two mirror, four reflection, ring field imaging system," OSA Proceedings on Extreme Ultraviolet Lithography, Frits Zernike and David T. Attwood, eds. (Optical Society of America, Washington, DC 1995), Vol. **23**, pp. 103-108.
5. B. La Fontaine, D.P. Gaines, D.R. Kania, G.E. Sommargren, S.L. Baker and D. Ciarlo, "Performance of a two-mirror, four-reflection, ring-field optical system operating at λ=13nm," these Proceedings.