Phase-shifting point diffraction interferometer

H. Medecki

Center for X-Ray Optics, Lawrence Berkeley National Laboratory, Berkeley, California 94720

E. Tejnil

Department of Electrical Engineering and Computer Sciences, University of California, Berkeley, Berkeley, California 94720

K. A. Goldberg

Center for X-Ray Optics, Lawrence Berkeley National Laboratory, Berkeley, California 94720, and Department of Physics, University of California, Berkeley, Berkeley, California 94720

J. Bokor

Center for X-Ray Optics, Lawrence Berkeley National Laboratory, Berkeley, California 94720, and Department of Electrical Engineering and Computer Sciences, University of California, Berkeley, Berkeley, California 94720

Received April 11, 1996

We describe a novel interferometer design suitable for highly accurate measurement of wave-front aberrations over a wide range of wavelengths, from visible to x ray. The new design, based on the point diffraction interferometer, preserves the advantages of the conventional point diffraction interferometer but offers higher efficiency and improved accuracy through phase shifting. These qualities make it applicable to at-wavelength testing of many optical systems, including short-wavelength projection lithography optics. A visible-light prototype was built and operated.

The desire for diffraction-limited optics places stringent requirements on the resolution and accuracy of interferometers used for optical metrology. Wave-front phase measurement at the operational wavelength of the optical system plays a key role in the characterization of system performance.

We present a novel phase-shifting point diffraction interferometer (PS/PDI) design that preserves the advantages of the conventional point diffraction interferometer (PDI) yet permits phase-shifting interferometry capability and significantly higher throughput. This compact, common-path interferometer generates the reference wave front by diffraction from a tiny pinhole and does not require reference surfaces or long coherence lengths. These features make the interferometer useful for accurate wave-front measurement over a wide spectral range. This instrument is being developed for accurate, high-resolution wave-front metrology of optics for extreme-ultraviolet projection lithography near the 13-nm wavelength.

A conventional PDI[1–3] is depicted in Fig. 1(a). In this simple design the test optic is illuminated with spatially coherent light and a semitransparent membrane, or mask, containing a tiny reference pinhole is placed near the focus. The mask transmits the test wave containing aberrations produced by the optical system, and the pinhole, which is smaller than the diffraction-limited focus of the test optic, diffracts a spherical reference wave front. The two wave fronts interfere, and the resulting interference fringe pattern can be recorded and analyzed to reveal aberrations in the optical system. For accurate analysis of the static fringe pattern a significant number of tilt fringes must be introduced by displacement of the reference pinhole laterally from the focus of the test optic. The resulting reduction of the light intensity incident upon the pinhole and the relatively small pinhole size necessitate a comparable reduction of the test wave intensity by mask attenuation. Inasmuch as the reference wave is produced by sampling of a small area of the test wave, there is no apparent way to introduce a variable relative phase shift between the two waves. One method for incorporating phase shifting by placing a transmission grating in contact with the pinhole mask and translating the grating with respect to the pinhole was reported previously.[4]

Two configurations of the novel PS/PDI design are depicted in Figs. 1(b) and 1(c). In each case the illumination is divided into two beams with a small angular separation. An opaque mask, placed near the focal plane of the test optic, contains one tiny reference pinhole and one large window centered on the respective foci of two beams. The subresolution reference pinhole produces the reference wave front by diffraction, and the window transmits the test wave without significant spatial filtering or attenuation.

Several factors contribute to the increased throughput of the PS/PDI design. Because the reference pinhole is now centered at the focus of one of the beams, the intensity of the diffracted reference wave relative to that of the conventional PDI is increased by several orders of magnitude. With the great increase in the reference wave intensity there is no longer a need to attenuate the test wave to match the intensities of the two interfering wave fronts. The large window in the

0146-9592/96/191526-03$10.00/0

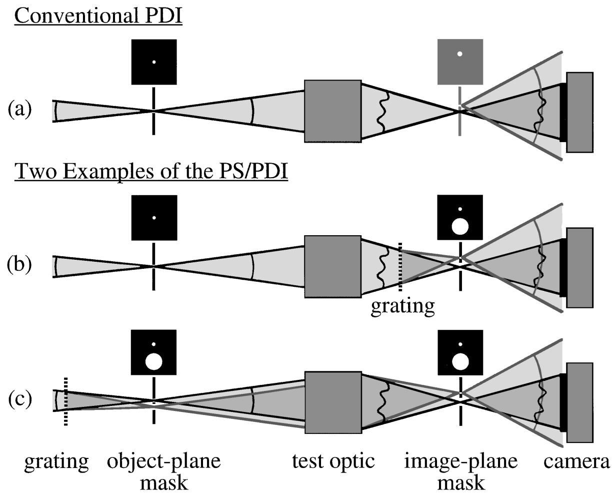

Fig. 1. Principle of optics testing with (a) the conventional point diffraction interferometer and (b), (c) the phase-shifting point diffraction interferometer. The PS/PDI utilizes a small-angle beam splitter (e.g., grating) and a two-pinhole spatial filter in the image plane. The illuminating beam is divided by a beam splitter that either (b) follows a single-pinhole entrance spatial filter or (c) precedes a two-pinhole entrance spatial filter.

image-plane mask delivers the full intensity of the test wave to the detector.

Beam division introduces the potential to vary the phase of one beam with respect to the other, permitting the use of phase-shifting interferometry. Beam splitting can be achieved in a number of ways and can be implemented either before or after the entrance pinhole. In Figs. 1(b) and 1(c) the wave front is divided with a coarse diffraction grating: a transmission or a reflection grating can be used. A two-pinhole mask selects only two of the diffracted grating orders to use as the test and the reference beams. Translation of the grating by one grating period introduces a first-diffractive-order phase shift of one full cycle while the phase of the zero-order transmitted beam remains constant. A grazing-incidence mirror can also be used as a wave-front divider. In this configuration the mirror surface can be rotated about the virtual source point to introduce a controlled relative phase shift between the two beams.

The lateral separation of the test and reference spots in the focal plane must be sufficient to prevent significant overlap. Without sufficient separation, a portion of the wave illuminating the reference pinhole can be transmitted through the test wave window, producing unwanted interference in the recorded fringes. However, as the separation is increased, high fringe density is produced in the interference pattern. Relatively unaberrated foci are needed to minimize the beam overlap for a given focal spot separation as well as to maximize the intensity illuminating the reference pinhole. Consequently the PS/PDI scheme is most useful for testing optics with relatively small aberrations.

Various PS/PDI designs can be divided into two subgroups. In the first group [e.g., Fig. 1(b)], the small-angle beam splitter follows the entrance pinhole spatial filter. In the second approach [e.g., Fig. 1(c)], beam splitting precedes the entrance pinhole. Here the aberrations that can be introduced by the beam splitting are filtered with a two-pinhole mask in the object plane, analogous to the two-pinhole mask located in the image plane. A subresolution pinhole, centered on one of the two beams, produces the spatially coherent illumination of the test optic while filtering any aberrations introduced by the beam splitter. A large window in the mask delivers the unattenuated light from the other beam, through the optic, to the reference pinhole in the image-plane mask. The second approach offers higher efficiency than the first because the beam that produces the reference wave front is filtered only by the image-plane mask.

Factors that determine the accuracy of the PS/PDI include the quality of the subresolution reference pinhole, the bandwidth and the spatial coherence of the illuminating beam, the accuracy of the introduced phase shift, and the spatial filtering caused by the mask window. Potentially the most challenging component to fabricate is the subresolution reference pinhole, which must be smaller than the diffraction-limited focal spot of the optic under test. However, a properly sized pinhole replaces the need for a reference surface. In the absence of a suitable laser light source the necessary bandwidth and coherence of the illumination can be obtained with an incoherent source with an appropriate monochromator and pinhole spatial filter. The PS/PDI configuration requires only a small angular beam separation. Consequently the required grating beam splitter is coarse, and the precision in the grating translation, which is a fraction of the grating pitch, is not difficult to achieve. The spatial filtering caused by the mask window through which the test beam passes determines the maximum spatial frequency that can be measured.

The interferometer is best suited to measuring imaging systems and optical components that produce converging wave fronts. High numerical aperture or aspheric element testing may require adaptations to prevent the interference fringe density from exceeding the spatial resolution of the planar detector. For example, accurate measurements of high numerical aperture systems may require a relay optic, introduced between the image-plane mask and the camera, to project the image of the pupil of the system onto the detector. A well-corrected relay optic would be needed to avoid introducing distortion into the recorded interference pattern and to minimize the difference in the optical paths of the test and reference waves, which propagate in slightly different directions through the relay optic.

To study the capabilities of the new interferometer we constructed a prototype PS/PDI system using visible light. We used several interferometer configurations that incorporate a grating beam splitter to measure aberrations in test optics, including microscope objectives and camera lenses. The simplicity of the design allowed us to construct this interferometer quickly, using readily available components and equipment.

In this proof-of-principle experiment a low-power helium–neon laser with 632.8-nm wavelength is used as a light source. The laser light is collected with a lens and focused onto an entrance pinhole mask that produces spatially coherent illumination of the optics under test. Commercially available laser-drilled pinholes are used for the single-pinhole and the two-pinhole masks. The entrance pinhole size is chosen to overfill coherently the numerical aperture of the test optic, and the subresolution reference pinhole size is selected to provide a strongly spatially filtered reference wave front. The grating used is a coarse Ronchi ruling.

One experiment performed with the prototype interferometer involved the measurement of a microscope objective lens. The lens was arranged to have a demagnification of 10× and an image-side numerical aperture of 0.1. A 100-μm-pitch beam splitter grating was placed upstream of the optic object plane, following the configuration shown schematically in Fig. 1(c). The entrance pinhole mask in the object plane contained a 20-μm-diameter pinhole to produce spatially coherent illumination of the optic and a 400-μm-wide window to transmit the second beam. The mask in the image plane contained a 2-μm-diameter reference pinhole and a 40-μm-wide window to transmit the test wave. The separation of the test and the reference wave foci in the image plane was $\sim$40 μm. The fringe patterns were detected with a 512 × 512 pixel, 6.2 mm × 4.6 mm, 8-bit CCD camera placed $\sim$2 cm from the image plane. This PS/PDI experiment was performed on an optical bench for stability. No measures were taken to isolate the system from thermal fluctuations or air turbulence.

To assess the repeatability and self-consistency of our measurements we measured the microscope objective at two different axial rotation orientations. In both positions a series of images with quarter-cycle phase shifts was recorded. Figure 2(a) shows one of the recorded fringe patterns. A nine-step phase-reconstruction algorithm was applied to the raw data, and the aberration phase map was fitted to the first 37 Zernike polynomials[5,6] over a circular region 480 pixels wide. Figure 2(b) is a contour diagram of the resulting phase map, with piston, tilt, and defocus removed.[6] The optic was rotated axially by 181° between the two measurements. A comparison of the measured aberration polynomial coefficients is shown in Fig. 2(c), where the largest uncertainty in the coefficients, based on the fit variance,[6–8] is 0.00016 wave. The coefficients of the second measurement were numerically rotated by 181° for direct comparison with the first measurement. The figure shows that the measured aberrations follow the rotation of the test optic, and the largest difference between the two sets of coefficients is 0.0050 wave. The rms difference between the two measured phase maps is 0.0037 wave, indicating self-consistent agreement to approximately $\lambda/250$. For this optic the wave-front variance[6] is of the order of 0.025 wave rms at 632.8 nm, revealing this interferometer's ability to characterize nearly diffraction-limited optics.

We have demonstrated an efficient phase-shifting point diffraction interferometer capable of accurate phase-measuring interferometry. The compact design and the relatively simple construction make this interferometer suitable for a broad range of measurement applications and wavelengths. We are in the process of applying this interferometer to testing of multilayer-coated reflective optics used in extreme-ultraviolet projection lithography.

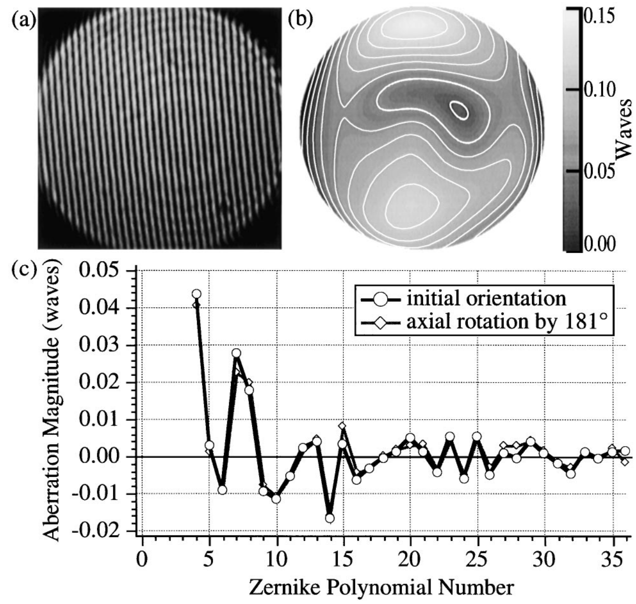

Fig. 2. Measurement of phase aberrations in a microscope objective lens with the phase-shifting point diffraction interferometer at $\lambda = 632.8$ nm. The measurement was performed for two rotational orientations of the lens with respect to the interferometer. For both orientations the recorded fringes (a) were analyzed to determine the wave-front phase map of the aperture of the optic (b). (c) The agreement of the Zernike polynomial fit coefficients for the two measurements indicates measurement self-consistency.

The authors thank D. T. Attwood for helpful discussions and suggestions. This research was funded by the Advanced Research Projects Agency Advanced Lithography program and by Semiconductor Research Corporation (contract 95-MC-500). We acknowledge the support of E. Tejnil by an Intel Foundation graduate Fellowship.

References

1. W. P. Linnik, Proc. Acad. Sci. USSR **1,** 208 (1933).
2. R. N. Smartt and W. H. Steel, Jpn. J. Appl. Phys. **14,** Suppl. 14-1, 351 (1975).
3. K. A. Goldberg, R. Beguiristain, J. Bokor, H. Medecki, D. T. Attwood, K. Jackson, E. Tejnil, and G. E. Sommargren, J. Vac. Sci. Technol. B **13,** 2923 (1995).
4. O. Y. Kwon, Opt. Lett. **9,** 59 (1984).
5. Code V Reference Manual, ver. 8.0 (Optical Research Associates, Pasadena, Calif.), p. 2A-335.
6. D. Malacara, ed., *Optical Shop Testing*, 2nd ed. (Wiley, New York, 1992), Chap. 13.
7. D. J. Fisher, J. T. O'Bryan, R. Lopez, and H. P. Stahl, Appl. Opt. **32,** 4738 (1993).
8. P. R. Bevington, *Data Reduction and Error Analysis for the Physical Sciences* (McGraw-Hill, New York, 1969), pp. 153–154.