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Erik L. Novak
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Christophe Gorecki
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Measuring the Phase Transfer Function of a Phase-Shifting Interferometer

Jiyoung Chu*[a,b], Quandou Wang[a], John P. Lehan[c,d], Guangjun Gao[a], and Ulf Griesmann[a]
[a]National Institute of Standards and Technology, 100 Bureau Drive, Gaithersburg MD 20899, U.S.A.;
[b]Korea Advanced Institute of Science and Technology, Daejeon, South Korea;
[c]Department of Physics, University of Maryland, Baltimore County, 1000 Hilltop Circle, Baltimore MD 21250, U.S.A.;
[d]NASA Goddard Space Flight Center, 8800 Greenbelt Road, Greenbelt MD 20771, U.S.A.

ABSTRACT

In characterizing the performance of a phase-shifting interferometer, the dependence of the measured height on the spatial frequency is rarely considered. We describe a test mirror with a special height relief that can be used to measure the height transfer function for the interferometer in a fashion analogous to the measurement of the modulation transfer function for the optical imaging system. We fabricated the test mirror at the National Institute of Standards and Technology (NIST) using a lithography-based process. The test mirror has several patterns (reminiscent of moth antennae) with variable spacing in radial direction. We describe the fabrication of the test mirror and its application to test the performance of the interferometer.

Keywords: Modulation transfer function, height transfer function, interferometer, lithography.

1. INTRODUCTION

A well known method for characterizing the performance of an optical imaging system is the modulation transfer function (MTF). It is the ratio of image contrast to object contrast as a function of spatial frequency. The MTF function thus is a measure of how well an optical system relays the image of an object at various spatial frequencies. Special test targets with high contrast patterns of various spatial frequencies are used to measure the modulation transfer function. Generally, the ability of an imaging system to transfer an image is diminished at high spatial frequencies and the image becomes blurred. In figure measuring interferometry one can similarly expect that height measurements made with interferometers are affected by the spatial frequency content of the measurand. Most applications of large aperture interferometers are measurements of smooth lens or mirror surfaces and so, only low spatial frequencies are of interest. Therefore, the transfer function of the interferometer, which describes the effect of spatial frequencies on the height (or phase) measurements, is rarely considered. Recently the need for measurements of complex structures with high spatial frequency content has increased and several new approaches for characterizing the response of interferometers to different spatial frequencies have been proposed. Test surfaces having patterns with various spatial frequencies[1], one-step patterns[2,3], and pseudorandom patterns[4] have been suggested for the performance evaluation of interferometers in height measurements.

In this paper, we describe the use of test mirrors with height patterns of varying spatial frequency to evaluate the height (or phase) transfer function of phase-shifting interferometers. In the second part of the paper, design and fabrication of the test mirrors using lithography processes will be described, and in part three, the height transfer function will be defined. In part four, test measurements for two different interferometers of the height transfer function using the test mirrors will be described. We describe the effect of defocus and lateral resolution of the CCD camera on the height transfer function of the interferometer. They are two of many parameters which influence the height measurement at various spatial frequencies

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2. PATTERNED TEST MIRROR FABRICATION

Unlike the test targets for the measurement of the modulation transfer function of an optical imaging system, a test surface for the measurement of the height (or phase) transfer function must have a well defined height profile which can be compared to the height measured by the interferometer. A lithography process was applied to fabricate a test mirror with known, nearly uniform height and known spatial frequency.

2.1 Pattern design

The entire pattern of the test mirror is inside a circle of approximately 140 mm diameter and is divided into twelve equal sections as shown in Fig. 1(a). Each section has one pattern with varying spatial frequency in radial direction. Three different patterns cover each quadrant of the test mirror; the patterns are repeated in each quadrant to fill the mirror surface. Pattern 1 (see Fig. 1(a)) has high spatial frequencies at intermediate radii and low frequencies near the center and the edge of the test mirror. Pattern 2 and pattern 3 have decreasing and increasing spatial frequencies in radial direction, respectively. The profiles of the three patterns are depicted in Fig. 1(b). In each pattern, all lines of different widths are connected to ensure correct phase unwrapping by the interferometer software within one pattern. The patterns are designed to have evenly distributed spatial frequencies as shown in Fig. 1(c). The spatial periods of the patterns range from 1 mm/cycle to 7.5 mm/cycle corresponding to 1 cycles/mm to 0.133 cycles/mm in spatial frequency, respectively. This type of pattern has several advantages. On a flat substrate, the surface profile typically changes most in radial direction while the variation in azimuthal direction is small. The height data of patterns on the substrate in radial direction can be determined easily. In addition, the performance of interferometer can be tested over whole aperture using symmetrically distributed patterns. After completion of the pattern design, a photomask was made by a commercial photomask supplier using e-beam lithography.

2.2 Lithography process

The substrate for the test mirror was a fused silica flat with 150 mm diameter and 20 mm thickness. The diameter is determined by the maximum size that can be patterned with the equipment at NIST's Nanofab. Many commercial interferometers have apertures diameters of 150 mm and the test mirror can be used to evaluate this type of interferometer. The thick substrate and fused silica material were chosen to reduce the deformation of substrate and the effect of temperature fluctuations. A lithography process was developed at the NIST Nanofab to transfer the pattern from

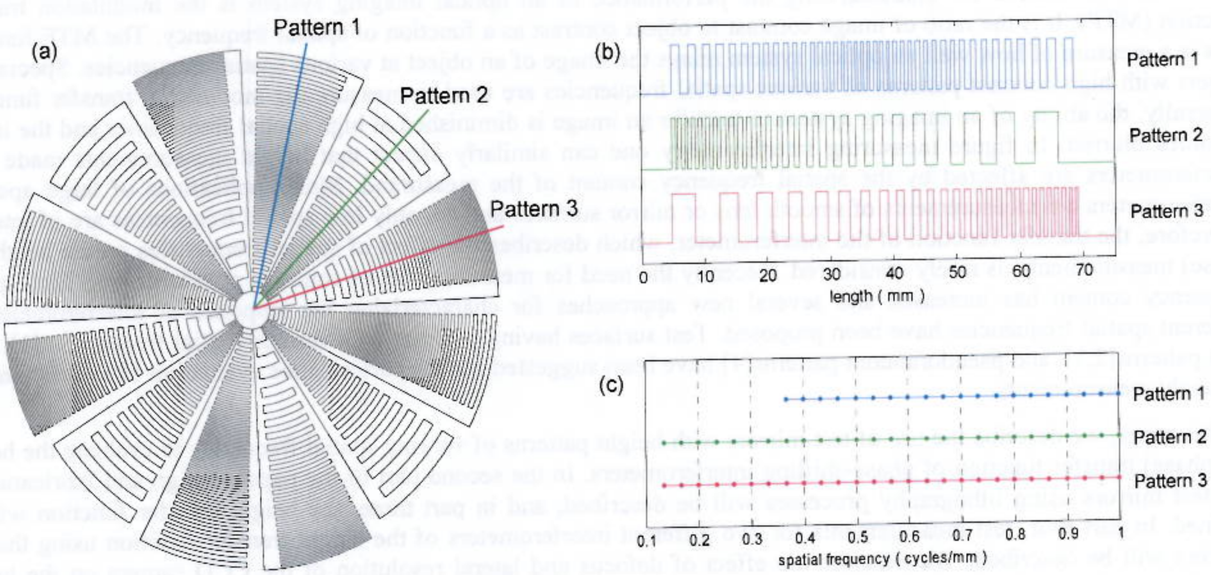


Fig. 1. The design of the test mirror. Three different patterns of varying spatial frequency along radial direction are disposed symmetrically with respect to the center of the test mirror, (a) the feature of the test mirror, (b) cross section profile of three patterns along radial direction, (c) spatial frequencies of three patterns

the photomask to the substrate. Because the substrates were thicker than the Si or SiO_2 wafers normally used as lithography substrates, the patterning process posed a considerable challenge. We made two test mirrors, one with a Cr surface and one with a fused silica surface. Fig. 2 shows the steps of the patterning processes.

For the fabrication of the first test mirror, a Cr layer of 100 nm thickness was deposited on the cleaned fused silica substrate. A positive photoresist was spin-coated on top of the Cr layer. The substrate was much heavier than a wafer and a relatively low rotation speed had to be used. As a result, the photoresist did not spread evenly on the Cr surface, making the photoresist coating the most difficult process step. The photoresist was then exposed in a mask aligner tool using a flood exposure mode. After developing the photoresist, the uncoated Cr areas were wet-etched using a commercial chromium etchant. This was followed by photoresist removal, which proved difficult due to the crosslinking and hardening of the photoresist by the Cr etchant. Finally a 20 nm thick layer of Cr was deposited to make the whole test mirror area reflective. The pattern height for the Cr coated test mirror was verified with a profilometer. It was found to be close to 100 nm.

An alternative method, the dry etching of the fused silica substrate, was also evaluated. After coating the silica substrate with a photoresist, exposure and photoresist development, the uncoated fused silica areas were etched using a reactive ion etching (RIE) tool. This process was simpler than the deposition based process used for the first test mirror, but it was more difficult to control the height of the patterns because the parameters for dry etching were different from ones used for wafers and the development of a deterministic etching process would have required additional substrates of the same size. The pattern height for the test mirror was about 40 nm. For both test mirrors, the heights of patterns are less than a half of the 633 nm wavelength, which make sure that problems due to phase unwrapping in the phase-shifting interferometers are avoided. The fabrication process guarantees a pattern uniformity error of less than 5 % for the whole

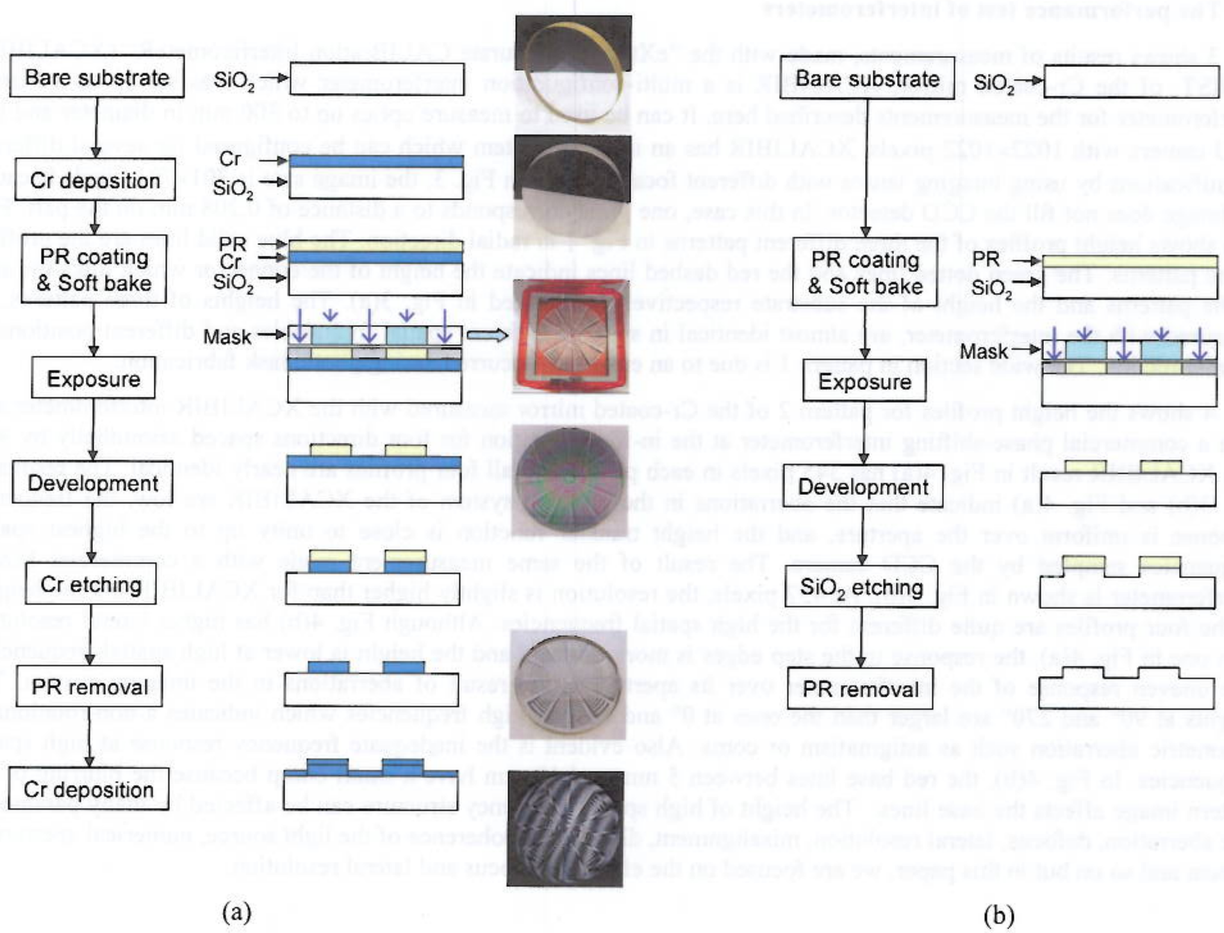


Fig. 2. Fabrication process of test mirrors in Nanofab, (a) Cr-coated surface, (b) fused silica surface

area.

3. HEIGHT TRANSFER FUNCTION

In phase-shifting interferometers, the measured height is directly related to phase, and the phase is calculated from intensity measurements using a phase detection algorithm. The detected fringe intensity is a function of light intensity and a sinusoidal function of height. In interferometers, it is not possible to consider the modulation transfer function independently of the phase transfer function and to evaluate the height response of interferometer separately from the optical imaging system. We define a height transfer function which describes the performance of the interferometer as a function of spatial frequency. The actual height of a structure on a part and the height as measured by an interferometer can be expressed as $h_s(r, \phi, \nu)$ and $h_m(r, \phi, \rho, \theta, \nu)$ respectively. Parameters r and ϕ are part coordinates in a polar coordinate system whereas ρ and θ are polar pupil coordinates of the optical system. Parameter ν is the spatial frequency. The height transfer function is defined as the height ratio of the measured height to the actual height as follows:

$$HTF = \frac{h_m(r, \phi, \rho, \theta, \nu)}{h_s(r, \phi, \nu)}. \tag{1}$$

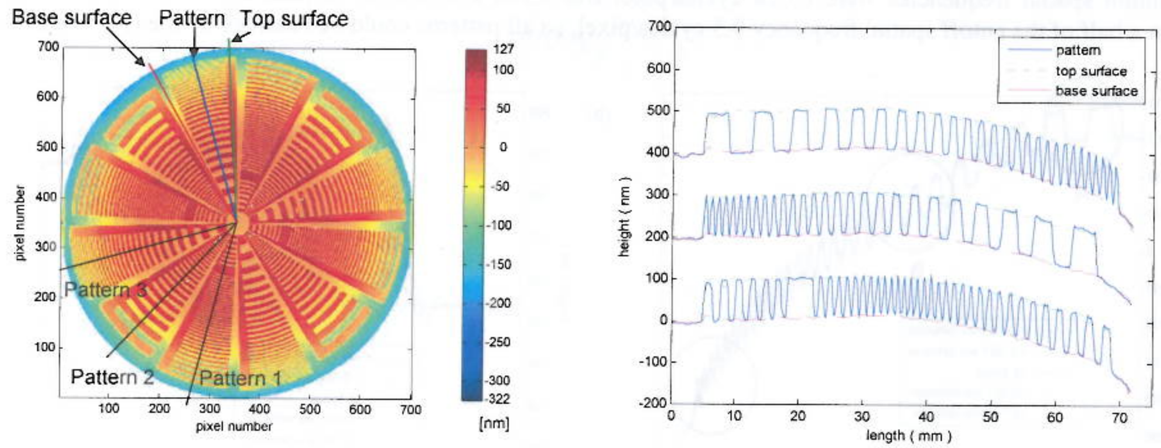
It yields information about the performance of height measurement made with the interferometer as a function of spatial frequency.

4. MEASUREMENTS

4.1 The performance test of interferometers

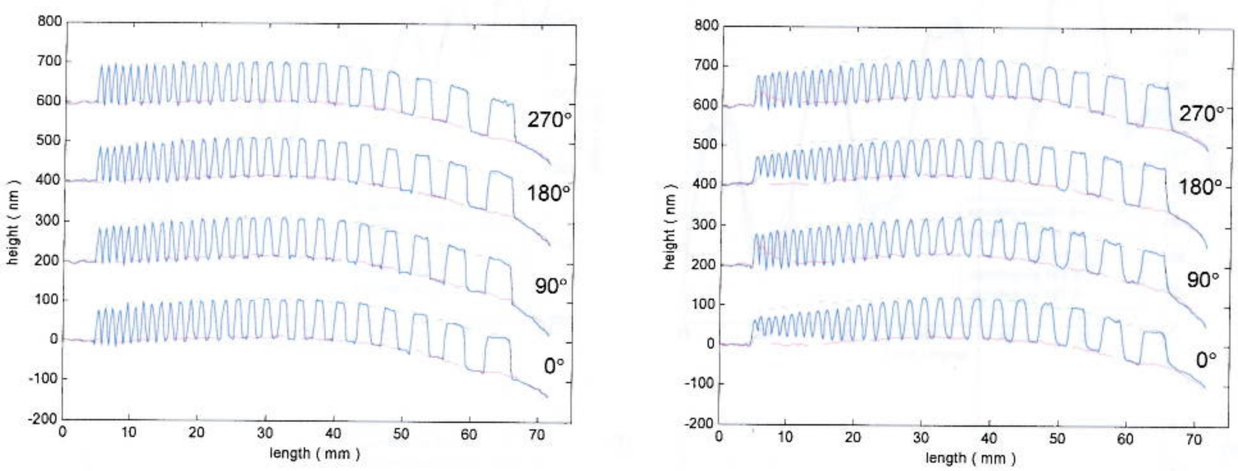
Fig. 3 shows results of measurements, made with the "eXtremely accurate CALIBration InterferometeR" (XCALIBIR) at NIST, of the Cr-coated mirror. XCALIBIR is a multi-configuration interferometer which was set up as a Fizeau interferometer for the measurements described here. It can be used to measure optics up to 300 mm in diameter and has CCD camera with 1022×1022 pixels. XCALIBIR has an imaging system which can be configured for several different magnifications by using imaging lenses with different focal lengths. In Fig. 3, the image size is 701×701 pixels because the image does not fill the CCD detector. In this case, one pixel corresponds to a distance of 0.208 mm on the part. Fig. 3(b) shows height profiles of the three different patterns in Fig. 1 in radial direction. The blue solid lines are the profiles of the patterns. The green dotted lines and the red dashed lines indicate the height of the connector which links the arcs of the patterns and the height of the substrate respectively as marked in Fig. 3(a). The heights of three patterns, as measured with the interferometer, are almost identical in spite of different spatial frequencies and different positions in radial direction. The wide section in pattern 1 is due to an error that occurred during photomask fabrication.

Fig. 4 shows the height profiles for pattern 2 of the Cr-coated mirror measured with the XCALIBIR interferometer and with a commercial phase-shifting interferometer at the in-focus position for four directions spaced azimuthally by 90°. The XCALIBIR result in Fig. 4(a) has 345 pixels in each profile and all four profiles are nearly identical. The results of Fig. 3(b) and Fig. 4(a) indicate that the aberrations in the imaging system of the XCALIBIR are low, the frequency response is uniform over the aperture, and the height transfer function is close to unity up to the highest spatial frequencies sampled by the CCD camera. The result of the same measurement made with a commercial Fizeau interferometer is shown in Fig. 4(b). At 457 pixels, the resolution is slightly higher than for XCALIBIR but the heights of the four profiles are quite different for the high spatial frequencies. Although Fig. 4(b) has higher lateral resolution than one in Fig. 4(a), the response to the step edges is more rounded and the height is lower at high spatial frequencies. The uneven response of the interferometer over its aperture is the result of aberrations in the imaging system. The heights at 90° and 270° are larger than the ones at 0° and 180° at high frequencies which indicates a non-rotationally symmetric aberration such as astigmatism or coma. Also evident is the inadequate frequency response at high spatial frequencies. In Fig. 4(b), the red base lines between 5 mm and 10 mm have a small bump because the blurring of the pattern image affects the base lines. The height of high spatial frequency structure can be affected by many parameters like aberration, defocus, lateral resolution, misalignment, diffraction, coherence of the light source, numerical aperture of system and so on but in this paper, we are focused on the effect of defocus and lateral resolution.



(a) (b)

Fig. 3. (a) Image of the height results for the Cr-coated mirror measured by XCALIBIR(imaging lens of f = 200 mm. Note that the image is inverted by the imaging system of the interferometer). (b) Cross section profile of three patterns along radial direction (blue solid line: pattern, green dotted line: top surface, red dashed line: base surface).



(a) (b)

Fig. 4. Height profiles of pattern 2 in four different directions (a) measured by XCALIBIR (pixel number = 345), (b) measured by a commercial interferometer (pixel number = 457), the height profile is distorted at high frequencies because of aberrations inherent in the imaging system.

4.2 The effect of defocus

In optical systems, defocus reduces sharpness and contrast of the image so the image appears blurred. In interferometers, defocus not only leads to loss of image sharpness and contrast, but also to errors in height measurements. When the height profile of the object is larger than depth of focus of the system in phase-shifting interferometers, even the measured height at best focus can result in the wrong value because of the defocus. The fused silica mirror with the pattern having 40 nm height was used to evaluate the effect of defocus at different spatial frequencies of the test mirror. Since this mirror is transparent, it was necessary to suppress the undesired reflection from the back side of the mirror. This could be done very effectively by coating the back side of the test mirror with a cosmetic face cream. This mirror was first measured at the in-focus position. Then the imaging system was defocused by moving the CCD camera along optical axis. An imaging lens with f = 200 mm was used. The resulting pixel spacing was 0.208 mm/pixel and minimum and maximum spatial frequencies were 0.028 cycles/pixel and 0.208 cycles/pixel respectively. All frequencies were lower than a half of the cutoff spatial frequency 0.5 cycles/pixel, so all patterns could be resolved by the CCD camera.

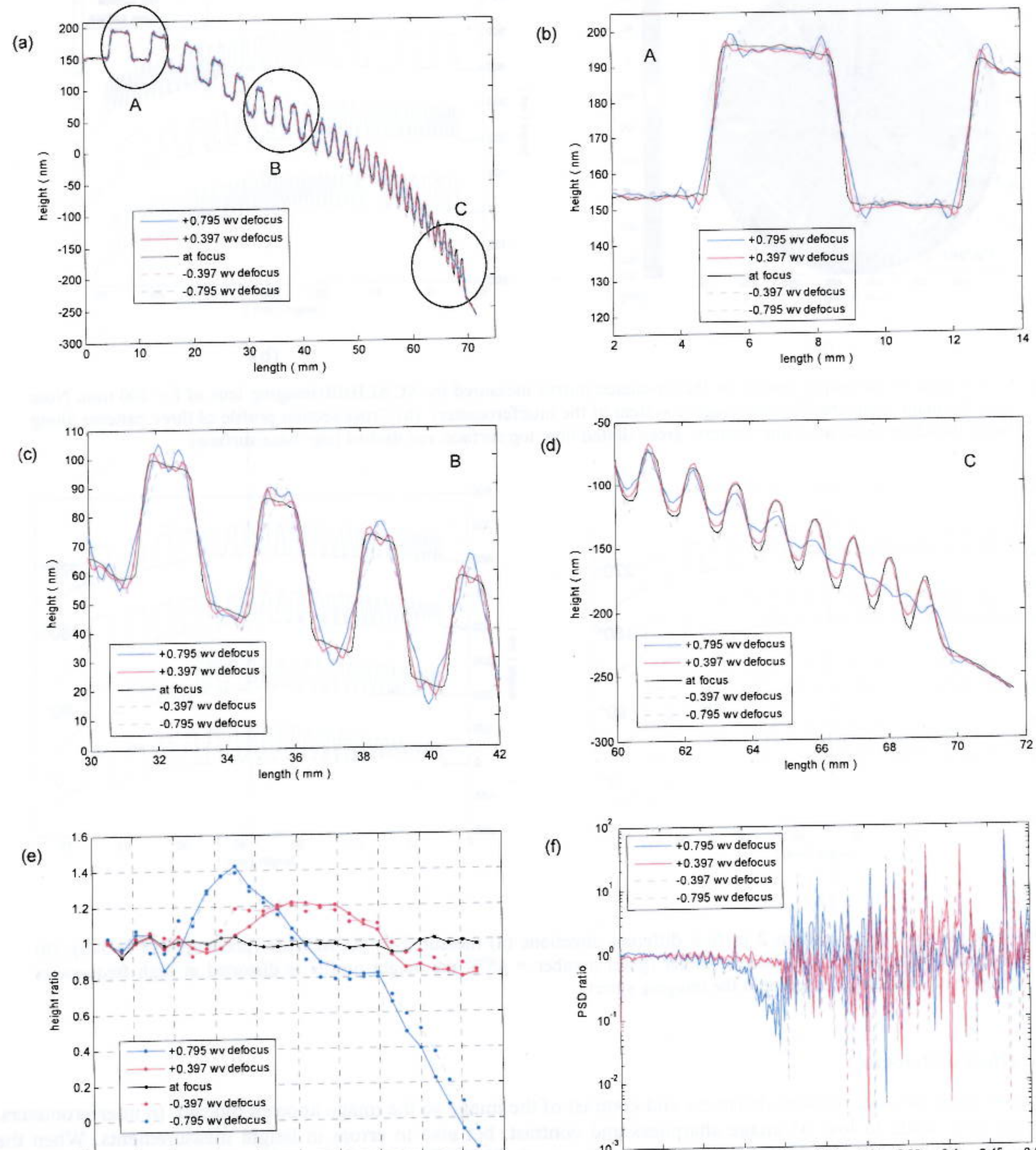


Fig. 5. Height profiles for pattern 3 of fused silica sample at focus and defocus positions measured by XCALIBIR (imaging lens of f = 200 mm, pixel number = 345), (a) height profile for the whole region, (b) low spatial frequency region, (c) intermediate spatial frequency region, (d) high spatial frequency region, (e) height ratio between interferometer data and stylus data with respect to spatial frequency, (f) power spectral density ratio of defocus height data to focus height data

The profiles of pattern 3 are shown in Fig. 5(a). The overall shapes of the patterns are almost identical but heights are changed as shown in Fig. 5(b), (c) and (d). In Fig. 5(b), defocus caused sharp fluctuations at the edges (Gibbs' phenomenon) at low spatial frequencies. Defocusing did not lead to significant height changes for wide lines. In Fig. 5(c), in regions with high spatial frequencies, a dramatic change in height is evident. As the spatial frequency of patterns increases, sharp fluctuations at the edges of patterns blend and the measured height becomes lower than the real height. After two peaks of edges are merged, the measured height becomes higher than the real height. In regions with higher spatial frequency, as shown in Fig. 5(d), the measured height decreases gradually although the spatial frequency is lower than a half of the cutoff frequency. For large values of defocus, the height measured by the interferometers is reversed at high spatial frequencies. Fig. 5(e) shows the measured height ratio of interferometer height to stylus data versus spatial frequencies at different defocus positions. Ideally, the height at focus should be same for the stylus measurements, but there are several reasons why these data are different. Measurement positions are not exactly same for the interferometer and the stylus. And the heavy sample made the stage of stylus profilometer unstable resulting in a high level of noise in the profilometer data. The height ratio of interferometer and stylus data is within 5 % of one at focus for 40 nm pattern height. As defocus gets larger, height change starts at lower spatial frequency and drop more quickly. The direction of defocus does not make much difference in height. Fig. 5(f) shows the ratio of power spectral density (PSD) for defocus height data to focus height data. In the case of ±4 mm defocus, the PSD ratio drops apparently in the range of 0.15 cycles/pixel to 0.2 cycles/pixel and for ±2 mm defocus, the ratio is slightly lower than other ratios in the range of 0.2 cycles/pixel to 0.25 cycles/pixel. The spatial frequency larger than 0.21 cycles/pixel is related to the rectangular edge in relief pattern and fluctuation on the pattern surface. The frequency loss caused by blurring of the image outside of focus results in height changes in regions with high spatial frequencies. However, the height of the pattern is determined by all spatial frequencies, especially in the case of rectangular profiles, and it is not easy to see the effect of spatial frequency on the height clearly from the power spectral density.

4.3 The effect of lateral resolution

The lateral resolution of interferometers is dependent on the number of CCD pixels and on the magnification of the imaging system. In this experiment, four imaging lenses were used; the number of CCD pixels is fixed. The focal lengths of imaging lenses are 200 mm, 150 mm, 125 mm and 100 mm. These imaging lenses result in pixel spacing of 0.208 mm/pixel, 0.276 mm/pixel, 0.332 mm/pixel and 0.415 mm/pixel respectively. The Cr-coated mirror with 100 nm pattern height was measured at focus for all imaging lenses. The maximum pattern size of 7.5 mm/cycle gives the lowest spatial frequency 0.028 cycles/pixel for f = 200 mm imaging lens and the minimum pattern size of 1 mm/cycle gives the highest spatial frequency 0.415 cycles/pixel for f = 100 mm imaging lens. This highest frequency is close to the cutoff frequency of the CCD camera 0.5 cycles/pixel.

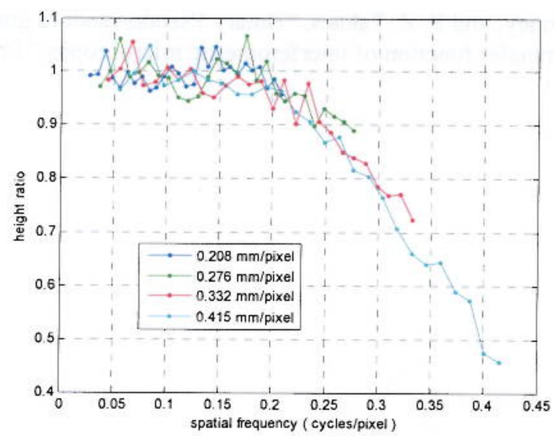


Fig. 6. Height ratio of pattern 3 of Cr-coated mirror to stylus data at focus with four different lateral resolutions

Fig. 6 shows height ratios, as a function of spatial frequency, for interferometric height measurements with four different imaging lenses divided by stylus profilometer data. When the spatial frequency is lower than half of the cutoff frequency(0.25 cycles/pixel in case of the f = 200 mm imaging lens), the height ratio is close to 1. But if the frequency is over 0.25 cycles/pixel, the ratio decreases. This means that even though one can recognize the pattern structure with high frequency, the height value could be wrong at low lateral resolution.

5. CONCLUSIONS

Test mirrors with a relief pattern of varying spatial frequency for the measurement of the height transfer function of phase-shifting interferometers were fabricated using lithography processes and the frequency response of phase-shifting interferometers was evaluated. Analogous to the modulation transfer function in imaging system, the height response of interferometers as a function of spatial frequency can be determined with the test mirror. Patterns of three varying frequencies can evaluate the performance of interferometers in radial direction of the interferometer aperture. Four identical patterns spaced at 90° can reveal asymmetries in azimuthal direction. If the interferometer does not have uniform performance over the entire aperture because of aberration or misalignment, the measured height is shifted or reduced in regions with high spatial frequency. The measured height is also sensitive to defocus and lateral resolution. In addition to the experiments shown in this paper, we plan to test the effect of coherence of the light source and material of sample surface using the test mirrors with varying spatial frequency. We expect that many properties of the interferometer can be tested using the patterned test mirrors.

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