Phase-Shifting Scatterplate Interferometer

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ABSTRACT

The advantages of common path interferometers for reducing effects of vibrations are well known. A scatterplate interferometer is one common-path interferometer that is well suited for the testing of large concave mirrors, however due to the common path characteristics it is difficult to perform phase-shifting. This paper describes a phase-shifting scatterplate interferometer where the phase-shifting is achieved by making use of the polarization characteristics of a birefringent scatterplate. The major advantage of this design is that it does not require any optical components to be placed near the surface under test. The theory of the interferometer is presented and experimental results are shown.

Keywords: Interferometry, Optical Testing, Metrology, Interference, Optical Measurements

1. INTRODUCTION

The computer has had a tremendous effect on optical testing the last twenty years, and in particular the powerful desktop computer has helped in the evolution of phase-shifting interferometry. In phase-shifting interferometry a series of interferograms are recorded while the reference phase is changed. The wavefront is encoded in the irradiance distribution of the fringe pattern and a simple point-by-point calculation in the computer recovers the phase. Some of the advantages of phase-shifting interferometry over other measurement techniques are high measurement accuracy, rapid measurement capability, and good results with low contrast fringes. Accuracies on the order of 1/1000 of a fringe are achievable. Phase-shifting interferometry was first conceived by Carré in 1966[1] and was more fully developed by many other investigators.[2, 3, 4] Phase-shifting interferometry provides greatly improved measurement accuracy. For phase-shifting interferometry the limiting error is usually set by vibration and air turbulence.

One way of reducing the sensitivity to the environment is to use a common-path interferometer such as the scatterplate interferometer. As the name implies, in a common path interferometer both the test and reference beams traverse the same optical path. In doing so both beams experience similar phase changes due to vibrations and air turbulence.

Unfortunately, the same feature that makes common-path interferometers desirable also makes phase shifting complicated. Since the test and reference beams traverse the same optical path, it is difficult to separate them for phase shifting. It is no longer feasible to place a phase-shifter in just one beam. The challenge then is to produce a variable phase difference between the test and reference beams.

In the case of the scatterplate interferometer two research groups have met this challenge: Huang et al and Su et al[5, 6]. Both methods use polarization to separate the test and reference beams by placing an auxiliary optic near the surface under test. Huang et al placed a small quarter-wave plate near the test surface that rotated only the incident linear polarization of the reference beam by 90°. With orthogonal polarizations in the test and reference beams the interferometer is phase shifted using an electro-optic light modulator. Su et al playing on the same theme placed a large polarizer with a small hole in the center near the test surface. In combination with additional polarization manipulating optics, the polarizer rotates the polarization of the test beam 90°.

The phase-shifting scatterplate interferometer presented in this paper also uses polarization to separate the test and reference beams. However, it does not require auxiliary optics to be placed near the test surface. The secret to this more practical approach is the use of a birefringent scatterplate to separate the test and reference beams. The birefringent scatterplate selectively scatters one polarization component of the incident beam while allowing the orthogonal component of

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polarization to pass directly through. Avoiding the placement of auxiliary optics near the test mirror allows the interferometer to be conveniently packaged.

First, a review of the conventional scatterplate interferometer will be presented. Then theory of operation for the phase-shifting scatterplate interferometer will be explored and experimental results will be examined.

2. CONVENTIONAL SCATTERPLATE INTERFEROMETER

The scatterplate interferometer is schematically a simple design. The configuration for testing spherical mirrors is shown in Figure 1. A small circular aperture is illuminated with a laser or broadband source producing a source of limited extent for the interferometer. A focusing lens is used to image the source onto the test mirror by way of a beam splitter that removes the source from the path of the return beam and a scatterplate. The scatterplate is placed at the center of curvature of the test mirror. Part of the light incident on the scatterplate scatters illuminating the entire mirror surface and part of it passes directly through imaging to a point on the test mirror. After reflecting off the test surface the light again propagates through the scatterplate scattering a portion of the beam. Finally, a focusing lens is used to image the interference fringes onto a screen or detector.

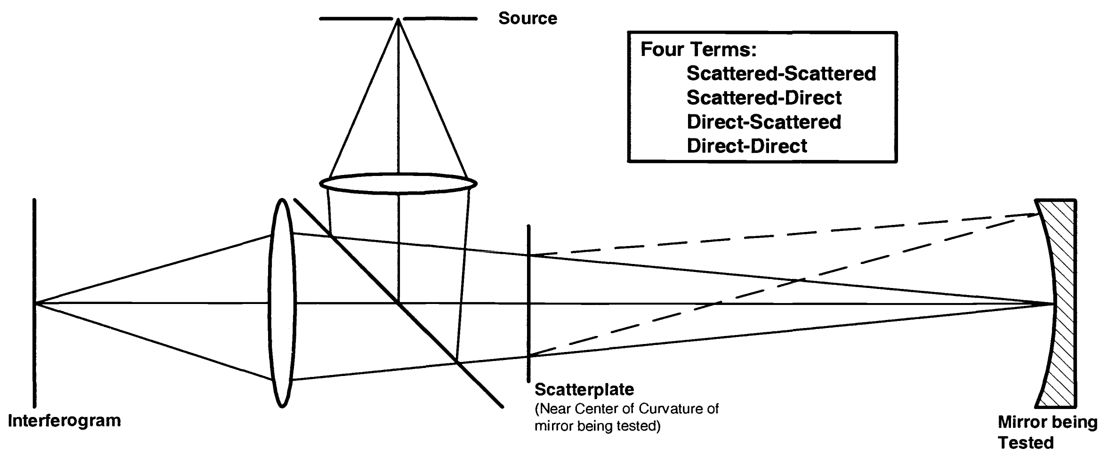

Figure 1: Scatterplate Interferometer for Testing Concave Mirrors

To understand what produces the interference fringes we need to look more closely at the effect of the scatterplate. Each time the light encounters the scatterplate some of it is scattered and a portion passes directly through the plate. Since the scatterplate is traversed twice there are four permutations of the beam that arrive in the image plane: 1) Scattered-Scattered, 2) Scattered-Direct, 3) Direct-Scattered, and 4) Direct-Direct. An examination of each of these combinations will uncover their role in producing fringes. The direct-direct beam passes directly through the scatterplate both times it is encountered forming an image of the source called the “hot spot” in the image plane. Since the “hot spot” is never scattered, it does not contribute to the production of interference fringes. Similarly, the scattered-scattered beam does not play a role in the formation of interference fringes. The light is scattered both times it passes through the scatterplate producing background irradiance in the image plane. The direct-scattered beam is the reference beam of the interferometer. The light passes directly through the scatterplate on the first pass and forms an image of the source on the test surface. If the image of the source is small enough the phase variations introduced into the beam on reflection are negligible. On the return leg the light is scattered. The scattered-direct beam serves as the test beam of the interferometer. The light is scattered on its initial pass through the scatterplate illuminating the entire test mirror. Any departures from a sphere will introduce phase variations in the beam. The light then passes directly through the scatterplate producing fringes when it interferes with the reference beam.

It seems unlikely that two beams of light that have been scattered at different positions in the interferometer could possibly produce interference fringes. In general, the process described above would not produce meaningful interference fringes, however if the scatterplate has inversion symmetry[7] interference fringes showing the quality of the mirror under test are obtained. Inversion symmetry means that each scatter point has an exact twin located directly opposite the center point of the scatterplate. The reason inversion symmetry works is revealed by examining individual scatter points and their effect on the reference and test beams. Keep in mind that examining individual points is not the complete story. Summing the wavefronts from all of the scatter points forms the contour fringes. Figure 2a summarizes the effect of inversion symmetry for a perfectly aligned system. When the incident light interacts with the scatterplate, the light scattered at scatter point S(x,y) acts like a point source. Since the scatterplate is located at the center of curvature of the test mirror, point S(x,y) is imaged back into the plane of the scatterplate at the conjugate point S'(x,y). The reference beam passes directly through the scatterplate reflects off the test mirror and scatters at point S(-x,-y). With inversion symmetry and proper alignment point S(x,y) and S(-x,-y) are scattered in exactly the same manner and the test and reference beams both appear as point sources located at point S(-x,-y). As a result, the phase change due to scattering is the same for both beams.

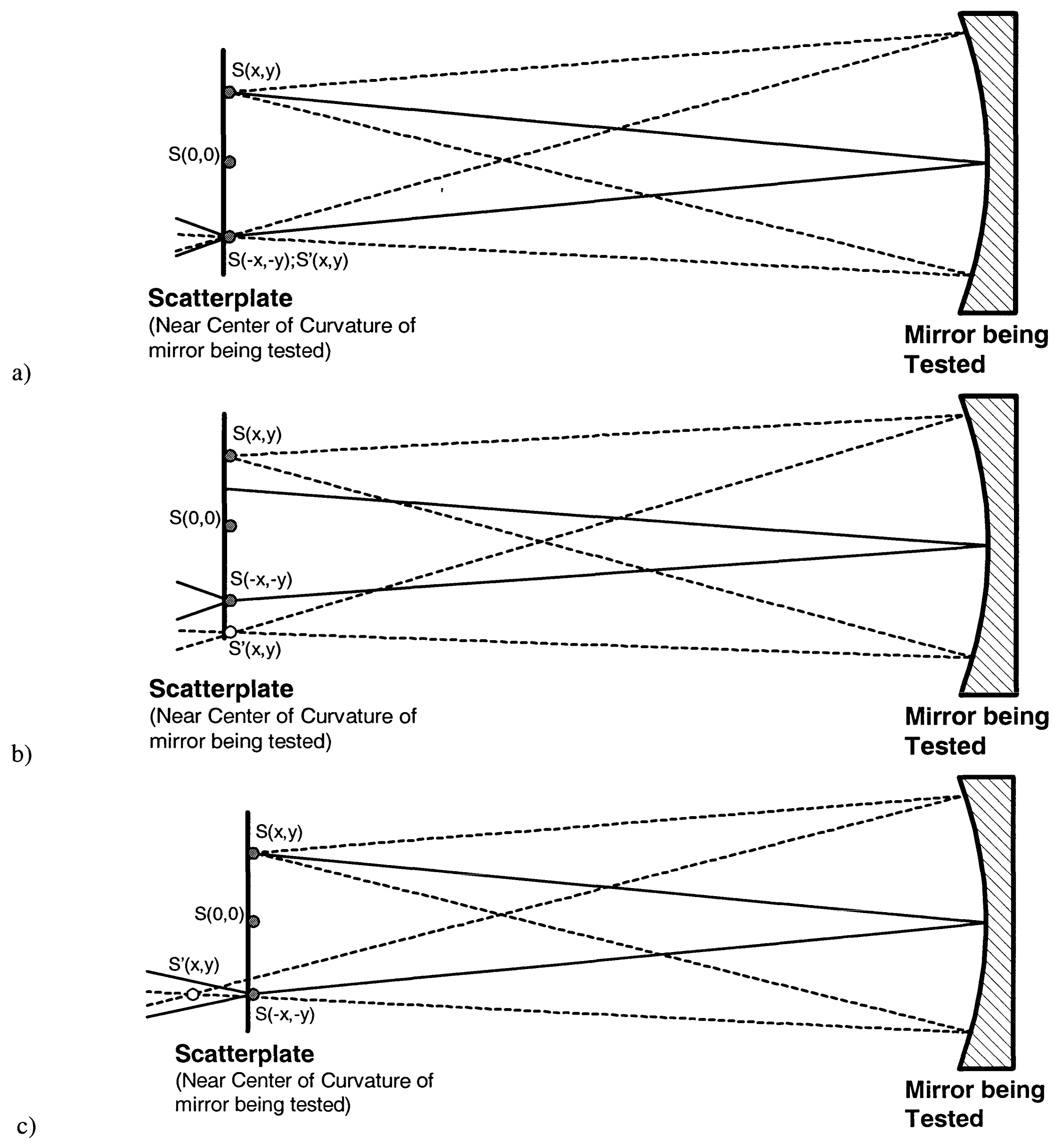

Figure 2: Point-To-Point Analysis of Inversion Symmetry: a) Perfect Alignment, b) Lateral misalignment of Scatterplate, c) Longitudinal Misalignment of Scatterplate

The above discussion of inversion symmetry was for a system with perfect alignment. The effect of misalignment of the scatterplate will now be discussed. Lateral movement of the scatterplate produces tilt in the contour fringes. Figure 2b demonstrates the consequence of not aligning the center point of the scatterplate with the axis of the interferometer. The image of S(x,y), although still in the plane of the scatterplate, no longer coincides with the symmetric point S(-x,-y). The result is tilt in the contour fringes produced by the interference of two laterally shifted point sources. Similarly, longitudinal misalignment of the scatterplate adds defocus to the contour fringe pattern. Figure 2c shows the effect of not placing the scatterplate at the center of curvature of the test mirror. The image of point S(x,y) is still at the same lateral position as the symmetric point S(-x,-y), however it no longer lies in the plane of the scatterplate. The interference of the two longitudinally shifted point sources produces defocus in the contour fringes. Adjusting the scatterplate position adds an important flexibility for minimizing the number of contour fringes across the image plane.

3. PHASE-SHIFTING SCATTERPLATE INTERFEROMETER

Before the operation of the interferometer as a whole can be understood it is necessary to independently examine the workings of the birefringent scatterplate. In the phase-shifting scatterplate interferometer, the goal is to control when the test and reference beams are scattered. Here the birefringent scatterplate shown in Figure 3 provides the desired control. The appropriate aperiodic pattern with inversion symmetry is etched into a calcite retarder using a chemical etching process. An index matching oil chosen to match the ordinary index of the crystal is then pressed between the calcite and a glass slide. The end result is that for light polarized along the ordinary axis of the crystal, the index of the oil and the index of the crystal appear the same and the light passes directly through the scatterplate, whereas light polarized along the extraordinary axis of the crystal sees an index difference and is scattered by the rough surface. This is the property that supplies the control over scattering necessary to phase shift the scatterplate interferometer.

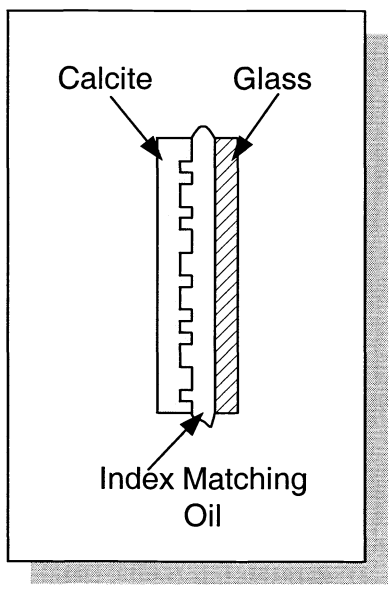

Figure 3: Birefringent Scatterplate

It is instructive to examine the operation of the phase-shifting scatterplate interferometer qualitatively. The schematic diagram of the interferometer is shown in Figure 4. If the polarization elements such as the wave plates and polarizers are removed, it is a conventional scatterplate interferometer discussed at length in the previous section. The polarizer passes linearly polarized light oriented at 45° with respect to the optic axis of the calcite scatterplate, providing equal amplitudes for the component of the beam polarized along the optic axis and the component polarized orthogonal to the optic axis. The component parallel to the optic axis will see the extraordinary index of the crystal and the perpendicular component will see the ordinary index. A liquid crystal retarder produces a variable phase shift between the two orthogonal components of polarization, and the rotating ground glass plate reduces the speckle in the interferogram by effectively enlarging the apparent source size. The source created at the ground glass plate is imaged onto the test mirror by way of the scatterplate and a quarter-wave plate oriented with its fast axis at 45° with respect to the optic axis of the crystal. The scatterplate is located at the center of curvature of the test mirror and scatters only the component of the beam that is polarized parallel to the optic axis of the crystal. The perpendicular component passes through the scatterplate and forms an image of the source on the test mirror. Both the scattered and direct beams pass through a quarter-wave plate twice producing a 90° rotation in the polarization of each. As a result, on the second pass through the scatterplate the beams change roles and the one that traveled directly through on the first pass is now scattered and the one that was scattered now passes directly through. The outcome is a scattered-direct and direct-scattered beam with orthogonal polarization. Finally, the test mirror is imaged onto a CCD array through an analyzer, which serves to combine the test and reference beams for observation of interference fringes. The end result is that the interference fringes can be phase shifted by applying a voltage to the liquid crystal retarder.

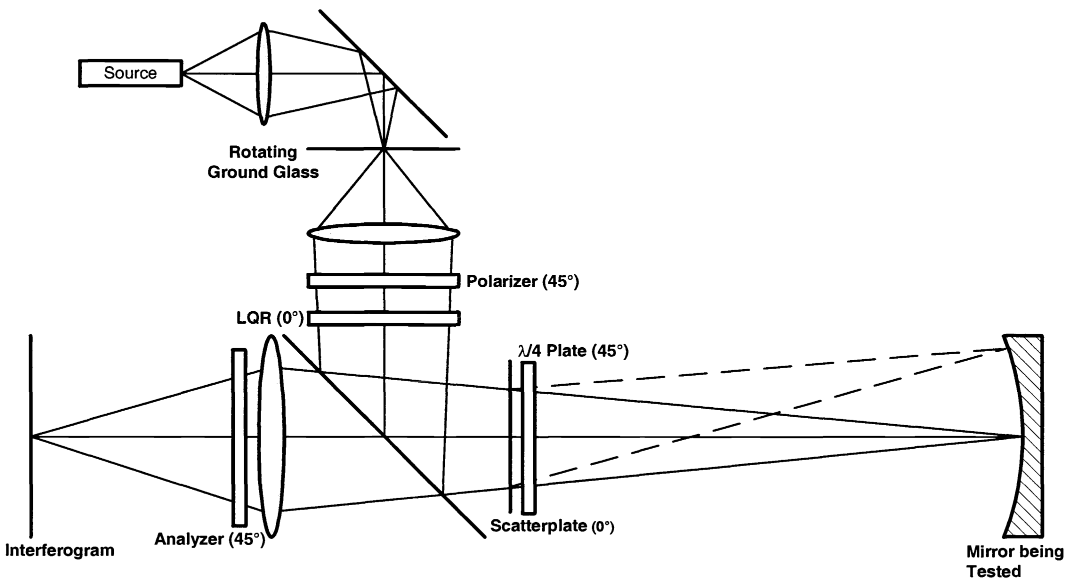

Figure 4: Phase-shifting Scatterplate Interferometer

4. PERFORMANCE

The performance of the interferometer was examined in two ways. First an F/6 test mirror with a focal length of 1.8m was measured using both the phase-shifting scatterplate interferometer and a commercial phase-shifting Fizeau interferometer. The resulting surface plots are shown in Figure 5. The difference between the two measurements was 0.0345 waves peak-to-valley. The missing data in the center of the scatterplate measurement is due to the “hot spot”. The second method for determining the performance was to determine the repeatability of the interferometer by subtracting two consecutive measurements. Figure 6 contains the subtraction. The RMS difference between two consecutive measurements is 0.0025 waves.

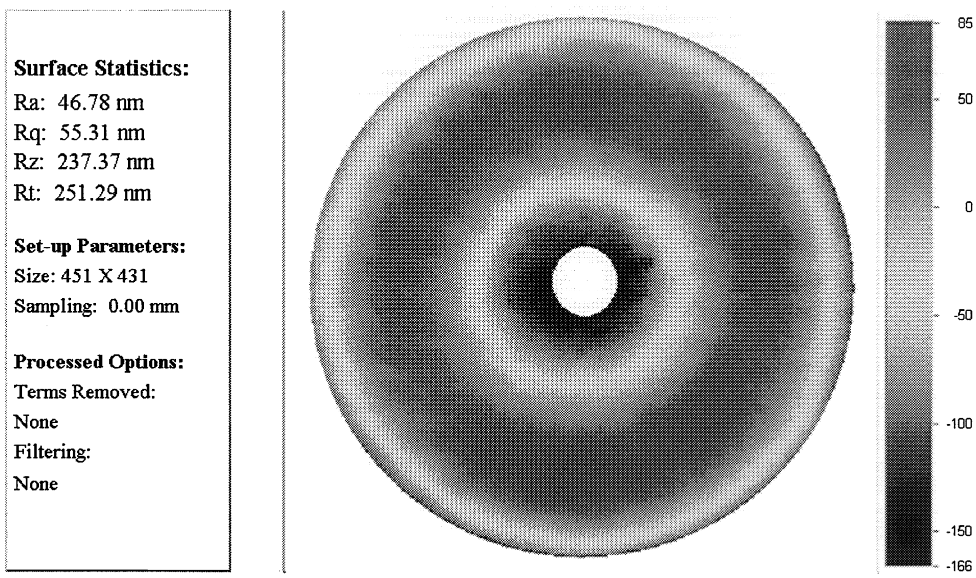

Figure 5a: Surface Measurement Taken With Phase-shifting Scatterplate Interferometer

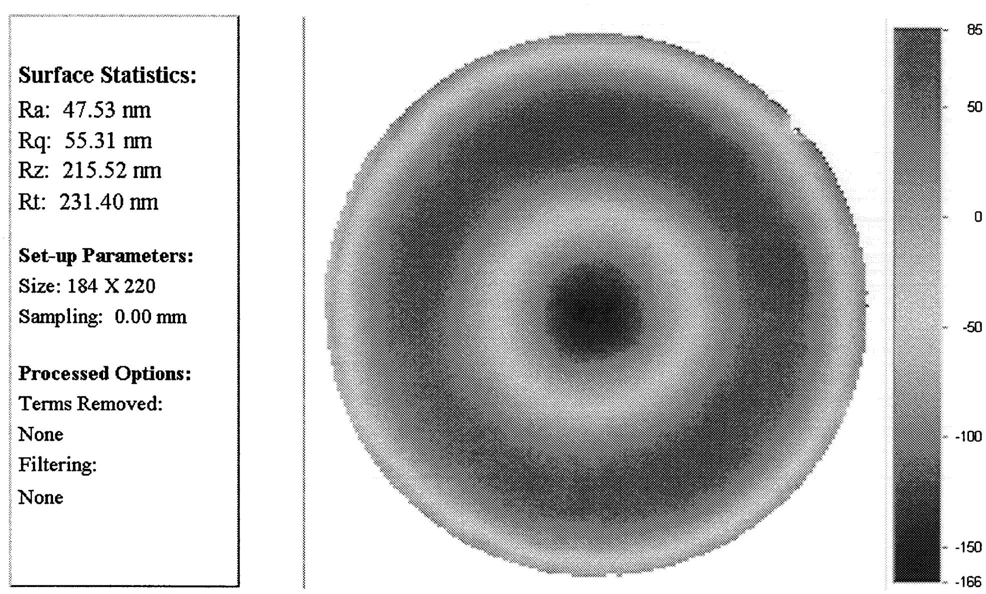

Figure 5b: Surface Measurement Taken with WYKO 6000 Phase-shifting Fizeau Interferometer

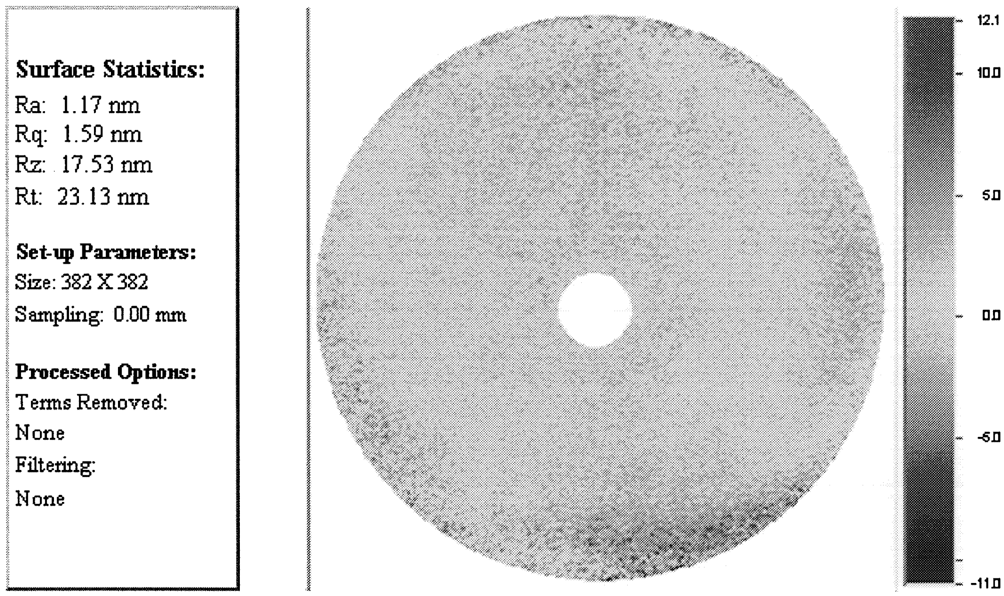

Figure 6: Subtraction of Two Measurements with Fringes "Nulled"

5. DISCUSSION

This paper describes and analyzes a new phase-shifting scatterplate interferometer. The interferometer separates the test and reference beams by exploiting the polarization characteristics of a birefringent scatterplate. The birefringent scatterplate was manufactured by etching the pattern into a good-quality calcite wave plate. The scatterplate scatters only the component of polarization oriented along the extraordinary axis of the crystal. Together with two polarizers and a quarter-wave plate, the birefringent scatterplate produces test and reference beams with orthogonal polarizations. A variable phase shift is induced between the beams using a liquid crystal retarder.

The performance of the interferometer was admirable. Subtracting two consecutive measurements demonstrated a repeatability of 0.0025 waves and comparing measurements with a commercial interferometer established a peak-to-valley accuracy of 0.03 waves, which was well within the uncertainty of the commercial interferometer measurement.

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