Optical Profiling Techniques for Characterizing Free-Form Optics

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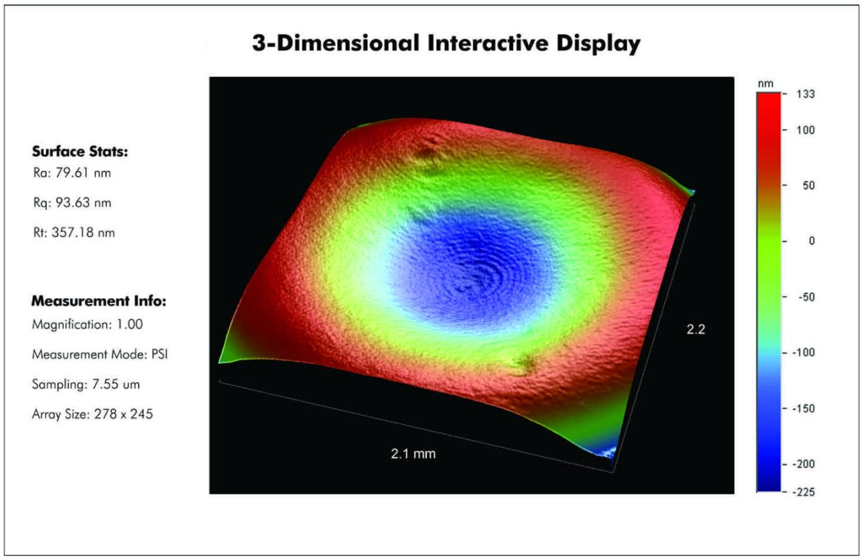

Figure 1. Aspheric element with a best-fit sphere subtracted from the final result, showing large differences between the two.

Introduction

Optics that deviate from the traditional spherical shape are increasingly popular in optical designs because of their superior image quality, reduced cost, and smaller space requirements. The increased availability of free-form optics is due in large part to improvements in optical manufacturing techniques such as diamond turning, ion beam milling, molding, computer controlled machining and fine-scale etching. Especially prevalent are smaller aspheric elements, which are incorporated into telecommunications systems, DVD players, MEMS and digital cameras.

Free-form optics pose unique challenges for process-control metrology, including larger slopes, steps, and overall heights. What's more, optical designs using free-form optics often use fewer elements, leaving fewer ways to compensate for surface figure error. This reduction demands tighter tolerances from the optical elements, which in turn require higher accuracy and repeatability from measurement equipment. Thirdly, new data analyses are required to characterize the quality of such optics, as many traditional metrics such as Zernike coefficients are not applicable.

Optical profiling (white light interferometry) offers a combination of resolution, speed and vertical range, which enables process-control measurement of the non-spherical surfaces which define free-form optics.

Measuring Larger Slopes

Free-form optics, including aspheres and diffractives, have dramatically larger slopes than spherical elements of the same diameter. Figure 1 shows an optical profiler measurement of an aspheric optic featuring significantly sloped areas. Capturing sufficient light to measure highly sloped surfaces requires microscope objectives with high numerical aperture and magnification. Such objectives, however, sacrifice field of view; to measure a large surface area then requires multiple measurements that are stitched together. New algorithms have recently been developed which enable stitching over a wide variety of surface shapes and slopes, while introducing residual errors below the noise floor of the instrument.

When measuring highly sloped and curved surfaces with an optical profiler, light from the test surface does not follow the exact optical path as light from the reference surface. This optical path difference has traditionally been accounted for by mapping the residual error and subtracting it from each part measurement. New software has been developed which allows a user to store a series of error maps taken from high-quality surfaces. The software then automatically subtracts these errors from subsequent measurements. With this improved method, nanometer-level accuracy is maintained, even over very steep test surfaces.

Measuring Larger Steps

Diffractive elements, and some silicon optics, contain large surface steps that also prove challenging for optical measurement. Phase shifting interferometry is limited to pixel-to-pixel height differences of less than approximately 160 nm, which is insufficient for measuring many free-form optics. Coherence-sensing techniques, such as vertical scanning interferometry, overcome this step height limitation but lack the accuracy of phase shifting.

A new technique developed by Veeco Instruments combines phase and coherence information to produce measurements with sub-nanometer noise over many microns of vertical range. This method has been further improved by the addition of an interferometric "reference signal" that tracks the scanner and adjusts for slight drifts that might occur during a series of stitched measurements. The combination of hardware and software enables high-fidelity characterization of surfaces with high steps or complex overall shape. Figure 2 shows an optical profiler analysis of a diffractive element measured with this technique. The very fine surface roughness is captured as well as the large surface steps.

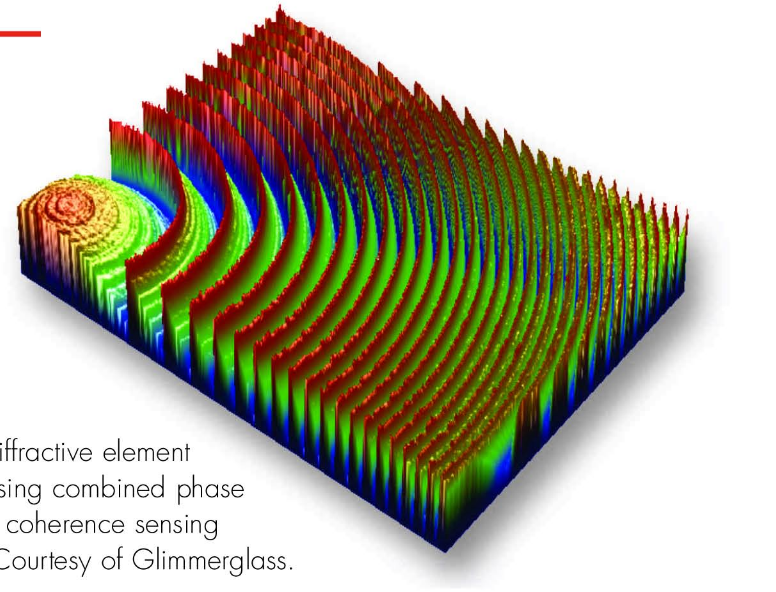

Figure 2. Diffractive element measured using combined phase shifting and coherence sensing technique. Courtesy of Glimmerglass.

Analyzing Free-Form Surfaces

Once surface data has been obtained, data analysis software is required to relate the surface shape to the optic's performance. Traditional Zernike analysis, typically employed for spherical optics, is not meaningful for many aspheric designs. Instead, the most common method is to analyze the difference between the designed and actual surfaces. Software has now been developed that can automatically subtract data taken from several widely used optical design software packages. Alternatively, given the part's aspheric coefficients, the software will automatically center and scale the theoretical data with respect to the actual data for proper subtraction. Once the difference is calculated, many analysis techniques can be performed on the result, including overall RMS roughness, power-spectral density, and pixel-by-pixel surface slope.

Other software techniques analyze the actual optic surface and calculate parameters such as the Strehl ratio, point-spread function, or bidirectional reflectance distribution function, to directly characterize its optical properties.

Increased Complexity and Tolerances

Analysis of free-form optics requires both highly accurate measurement hardware and flexible software for proper data analysis. As these optics become even more prevalent, production-floor metrology for their process control will become even more critical. The demands of increased design complexity and tighter tolerances will continue to drive improvements to interference microscopes that will enable such elements to be employed in a greater array of applications.

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