Radius Measurement of Spherical Surfaces With Large Radii-of-Curvature Using Dual-Focus Zone Plates

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Abstract: The measurement of spherical surface radii exceeding few meters presents a challenge, because the familiar radius-bench method requires large part displacements. Dual-focus zone plates can extend the radius-bench method to measurements of large radii.
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1. Introduction

The complete characterization of a spherical surface requires the measurement of the radius-of-curvature (ROC) of the ideal best-fit sphere and a measurement of the sphericity, which is a map of the deviation of the surface from the best-fit sphere. ROC measurements with low measurement uncertainty are frequently made with the interferometric radius bench method. A modern interferometric radius bench combines a phase-shifting interferometer with a displacement measuring interferometer which tracks the position of the spherical part under test along the optical axis [1,2]. For the measurement of the radius, a spherical part is first positioned such that its center of curvature is near the focus of the spherical test beam (confocal position), as is shown in Fig. 1. The exact confocal position is measured with the displacement measuring interferometer (DMI) and the phase-shifting interferometer (PSI). The part is then moved along the optical axis until the focus of the test beam is close to the part surface (cat's-eye position). The distance between the confocal and cat's-eye positions is the radius of the spherical surface (see Fig. 1). Clearly, the radius bench method becomes impractical when the part radius exceeds few meters, because a very long radius bench is required. The same limitation applies to measurements of the sphericity, or form error. Interferometric form error measurements are usually performed at the center of curvature which also becomes impractical when the part radius is very large. In addition, atmospheric turbulence in the beam path and vibration tend to degrade the measurement uncertainty for both radius and form error measurements [3]. Few methods for measuring large radii have been described. One method, applicable to concave surfaces with *very* large radii, was described by Gerchman and Hunter [4]. In this method interferometer cavities are formed between the part under test and a flat reference mirror. Spherical surfaces with intermediate radii, which are too large to be measured using a radius bench but too small to be measured against a reference flat, present the greatest challenge.

2. Radius Measurements with Zone Plates

We describe here a novel method for the ROC measurement of spherical surfaces using dual-focus zone plates which is particularly useful for the measurement of intermediate radii. In this method, the transmission sphere in the radius bench is replaced with a dual-focus zone plate as shown in Fig. 2. The zone plate is fabricated to have two first-order focal lengths f_1 and f_2. For a concave test part, as is shown in Fig. 2, the focal length f_1 is chosen such that the large-radius test part can be positioned at the confocal position for the -1^{st} diffraction order. This position is measured using a combination of DMI and PSI as in the conventional radius-bench method. The test part is then moved until the focus with focal length f_2 is near the test part surface. The distance *d* between this cat's-eye position and the initial confocal position is measured with the DMI. The radius *R* of the test part is related to the distance measurement and the focal lengths of the zone plate as follows (see Fig. 2):

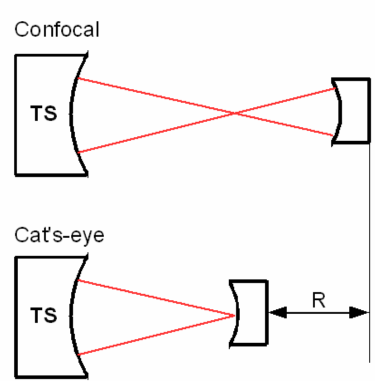

Figure 1: Radius-bench method

$$R = f_1 + f_2 + d\ . \qquad (1)$$

The focal lengths of the zone plate can be determined from the distance Δ of any two foci belonging to positive diffraction orders N^a and N^b:

$$\Delta_k = \left(\frac{f_k}{N_k^a} - \frac{f_k}{N_k^b} \right),\ k = 1,2 \qquad (2)$$

where $N^b > N^a$. Once Δ_1 and Δ_2 are measured, f_1 and f_2 can be determined using Eq. 2 and then the radius R, using Eq. 1.

For the faster beam with focal length f_2 the first and third diffraction orders can typically be used to measure the focal length. Higher orders must be used for the beam with the large focal length f_1, which can be problematic because of the drop in diffraction efficiency for the higher orders of a zone plate. For example, the highest possible diffraction efficiency for the first order of a phase zone plate is about 40%, but the efficiency for the $\pm 7^{th}$ orders of the same zone plate is only 0.8% [6]. Since the beam must be diffracted twice at the zone plate for the measurements of the Δ_k, the efficiency for higher orders may be insufficient for practical measurements. If the diffraction efficiency proves insufficient, it is necessary to rely on the fabrication tolerance of the zone plate for an estimate of the focal lengths and their uncertainties.

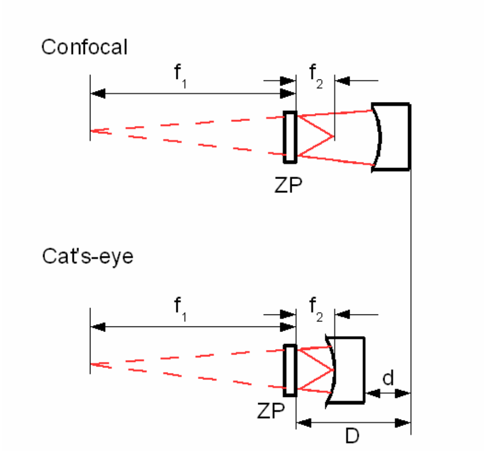

Figure 2: Radius-bench method with zone plate.

3. Zone Plate Fabrication

Dual-focus zone plates can be fabricated in several ways. Here we describe a nested dual-focus zone plate like the one shown in Fig. 3 which was used to measure the radius of a concave spherical mirror with 50 mm diameter and a nominal radius of 10 m. The Fresnel phase zone plate at the center of the nested zone plate (see Fig. 3) has a diameter of 10 mm and a focal length of 190 mm. The outer region of the zone plate between 10 mm and 50 mm radius is a Fresnel phase zone plate with a focal length of 9810 mm. Based on the design data of the zone plate, a chrome-on-glass photomask was made by a commercial photomask manufacturer using e-beam lithography. We fabricated the nested zone plate shown in Fig. 3 at the Nanofab facility of the Center for Nanoscale Science and Technology (CNST) at the National Institute of Standards and Technology (NIST) using a photo-lithography process. A fused silica substrate with 50 mm diameter and a thickness of 6 mm was spin-coated with a photoresist. The zone plate pattern was then transferred from the photomask onto the coated substrate with a mask-aligner tool. After developing the photoresist, the zone plate pattern was etched into the substrate using a reactive ion etching (RIE) process. We fabricated zone plates with different etch depths. For example, one zone plate was etched to a depth of 688 nm, corresponding to a phase difference of one wavelength between adjacent zones, to achieve the highest possible diffraction efficiency of 40% for the first diffraction order [7]. The pattern height uniformity was measured with a stylus profilometer. The maximum pattern height difference was approximately 30 nm. Since excellent height uniformity is desirable, but not easy to achieve with an RIE process, alternative methods for the fabrication of the zone plates were also explored. 688 nm thick layers of silicon dioxide were deposited with either plasma-enhanced chemical vapor deposition (PECVD) or

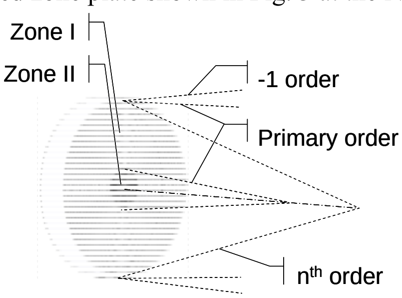

Figure 3: Design of a nested dual-focus zone plate

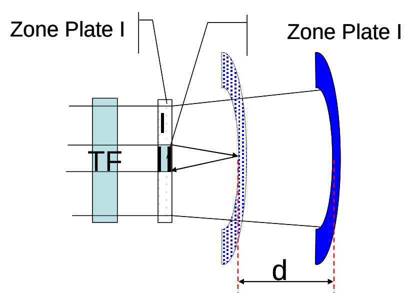

Figure 4: Dual-focus zone plate radius bench setup

sputter coating on a dielectrically coated substrate. The layers were then patterned using photolithography and etched. Because the dielectric coating on the substrate has a very low etch rate for RIE, it acts as a stop layer for the etching process. With this process, very good pattern height uniformity, limited only by the coating uniformity, can be achieved. The PECVD deposition is much more efficient than the sputter coating. A 688 nm thick layer could be deposited in about 15 minutes whereas approximately three hours were needed to deposit the layer using sputter coating. The layer deposited with PECVD also had better uniformity and the zone plate made with this process performed better.

4. Conclusion

We have developed a method, based on dual-focus zone plates, for measuring the radii of spherical surfaces having large radius-of-curvature with interferometry. The zone plates were made at the Nanofab at NIST's Center for Nanoscale Science and Technology. Initial measurements of the radius of a mirror with a nominal radius of 10 m using a nested dual-focus zone plate are promising. Other zone plate designs in which the spherical wavefronts with both focal lengths are emitted over the entire area of the zone plate are also being explored because they allow for quasi-absolute calibration of the wavefronts transmitted by the zone plate [8].

Acknowledgments

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