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Low-coherence interferometer for contact lens surface metrology

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Abstract. Contact lens performance depends on a number of lens properties. Many metrology systems have been developed to measure different aspects of a contact lens, but none test the surface figure in reflection to subwavelength accuracy. Interferometric surface metrology of immersed contact lenses is complicated by the close proximity of the surfaces, low surface reflectivity, and instability of the lens. An interferometer to address these issues was developed and is described here. The accuracy of the system is verified by comparison of glass reference sample measurements against a calibrated commercial interferometer. The described interferometer can accurately reconstruct large surface departures from spherical with reverse raytracing. The system is shown to have residual errors better than 0.05% of the measured surface departure for high slope regions. Measurements made near null are accurate to $\lambda/20$. Spherical, toric, and bifocal soft contact lenses have been measured by this system and show characteristics of contact lenses not seen in transmission testing. The measurements were used to simulate a transmission map that matches an actual transmission test of the contact lens to $\lambda/18$. © 2016 Society of Photo-Optical Instrumentation Engineers (SPIE) [DOI: 10.1117/1.OE.55.3.034106]

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1 Introduction

Soft contact lenses are intrinsically difficult to characterize. They quickly dry out in air and change shape. Several efforts have been made to test and qualify contact lenses in air,^{1–3} but the accuracy is limited by these deformations. Measurements must be performed in solution to determine the true shape of the lens. The index of refraction of the contact lens nearly matches the index of refraction of the saline solution, which reduces the Fresnel reflectivity of the lens surfaces to 0.06%. This is one of the major reasons submerged contact lenses are not typically measured in reflection.

Metrology systems have been developed to measure contact lenses in solution but do so in transmission.^{4–8} Transmission tests provide important information about the contact lens but do not differentiate between features in the index of refraction and features on the surfaces. Features from both surfaces are combined in one measurement. This makes it difficult to identify the source of manufacturing variations. Features seen in transmission could come from bulk refractive index variation or topography of either side of the lens. In order to determine the origin of features in a transmission test, the surfaces of the contact lens need to be measured. This information, along with several other measurements, will provide a full description of the lens, which is referred to here as “whole lens reconstruction.”

The index of refraction for both the immersion solution and contact lens material needs to be known to relate a transmission test to surface measurements. Systems have been designed recently to measure these quantities. The index of refraction of saline solution was characterized by a

Hilger–Chance type refractometer.⁹ This system measures the refractive index to 0.0001 accuracy. The index of refraction of the contact lens material was determined by a dual interferometer system.^{10,11} It uses a low-coherence Twyman–Green interferometer along with a Mach–Zehnder interferometer in transmission to measure the phase and group indices of refraction to an accuracy of 0.0001. The thickness is also required for a full description of a contact lens and has been characterized in several ways,^{12,13} but it will also be determined by the interferometer described in this paper. The main purpose of the interferometer described in this paper is to provide surface measurements of a submerged contact lens in order to perform a whole lens reconstruction.

2 Interferometer Design

The system is a low-coherence polarization-splitting Twyman–Green phase-shifting interferometer. The interferometer will be referred to as LOCOH in reference to its low coherence. Figure 1 shows the system layout. The entire interferometer is built on a vertical breadboard so the contact lens can rest on a horizontal surface.

The source is a fiber-coupled superluminescent diode that is collimated through a half-wave plate, optical isolator, and focused into a spatial filter. The expanding wavefront is collimated and divided by a polarizing beamsplitter into the test and reference arms. Contact lenses are typically 70 to 150 μm thick and the surfaces are nearly concentric. Both surfaces can be measured relative to a best fit sphere with little motion of the contact lens. The measurement of the convex surface of the contact lens (the anterior surface) will be made through the concave surface of the lens (posterior surface). However, a conventional laser source has a coherence

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Fig. 1 System layout.

length much longer than the thickness of the lens, and fringes would be observed for both surfaces simultaneously. A low-coherence source can be used so that fringes are only observed for one surface at a time. The source used is centered at 650 nm and has a coherence length of about 56 μm , which is sufficiently short to isolate each surface.

The test path consists of a quarter-wave plate followed by the transmission sphere. The final surface of this lens assembly interfaces directly with the saline solution. The transmission sphere is designed to produce a nearly spherical ($\lambda/10$) wavefront in saline. The contact lens is supported by a glass plate with a hole in the center for the transmission sphere to focus through. The position of a mirror attached to the contact lens mount is tracked with a distance measuring interferometer to measure the distance between cat's eye and confocal measurements in order to determine the thickness and radius of curvature of the surface.^{14–16} Figure 2 shows a close-up of the saline cuvette and the contact lens mount. The saline cuvette consists of the transmission sphere lenses as well as the saline tank on top. The mount for the contact lens is attached to a three-axis motorized translation stage so that the lens can be aligned to the interferometer.

The custom designed and fabricated transmission sphere or diverger lens forms the bottom of the test cuvette.¹⁷ The nominal radius of curvature of the concave surface of a contact lens is about 8 mm, and the NA of this lens was chosen to provide a measurement zone of 6 mm diameter on the contact lens surface. The detector used in the interferometer is 1458×1936 pixels, providing a spatial resolution of about 2.5 μm on the surface. Reverse raytracing allows surface

reconstruction as long as the fringes do not alias. The resolution of the detector then limits the maximum measurable departure from a sphere to 384 waves per radius or a maximum sag of 314.6 μm . The actual area and resolution measured on a surface depend on the radius of curvature and the

Fig. 2 Transmission sphere and cuvette assembly for the test path.

number of rays used in reverse raytracing. For the results shown here, rays are traced from each pixel but are binned to give a consistent resolution of $10\ \mu\text{m}$ for all surfaces.

The use of a low-coherence source adds complexity to the design by requiring reference path compensation. The reference path must pass through the same amount of dispersive materials as the test path for maximum fringe visibility. This includes matching the path length through the transmission sphere and saline solution. Since different radii contact lens surfaces are to be measured, the saline path length needs to be variable in both the test and reference arms. In order to minimize the number of interfaces in the reference path, a prism is partially submerged in saline. Changing the depth of submersion changes the reference path length in solution. The back surface of the prism is the reference surface so that only three interfaces are encountered in the assembly. The window and prism are also wedged to minimize stray light. The thicknesses of the prism and the window are selected to match the path length and dispersion of the transmission sphere in the test path. The reference tank assembly is shown enlarged in Fig. 3.

The surfaces of a contact lens submerged in solution have very low reflectivity. The index match between the solution and the contact lens material results in a reduced Fresnel reflectance. Based on measurements of the lens material^{10,11} and saline,⁹ the power reflectivity of either contact lens surface is only 0.06% at the wavelength of the source. Each air–lens interface in the transmission sphere has nearly four times the reflectivity, even with 0.25% anti-reflection coatings. Stray light management is critical in this design. Since the surfaces of a contact lens are nearly concentric, reflected light from both contact lens surfaces will reach the detector even with stringent stray light mitigation. Only one surface reflection will interfere with the reference wavefront, but the second surface reflection will reduce the maximum fringe modulation by 33%. Other sources of stray light, vibration, or dispersion further reduce the fringe modulation.

The interferometer uses polarization splitting to divide the irradiance between the test and reference paths. The amount of light returned from the reference surface needs to match the amount of light from the contact lens for good fringe

modulation. This method allows the division of irradiance to be tuned by rotating the linear polarization state of the source. The reference surface is bare glass, which reduces the required polarization splitting ratio, but a ratio of $\sim 70:1$ is still required. This ratio is attainable with high-quality polarization elements. Polarization-splitting interferometers use quarter-wave retarders in the reference and test arms to rotate the polarization state by 90 deg after double passing through the retarder. The reflected light from each arm of the interferometer can then be recombined in the imaging path. Any light that does not double pass through the retarder is rejected by the beamsplitter and is sent back to the source.

The surface shapes measured by this interferometer will vary with contact lens design and will often have large departures from spherical. The variation of surface shapes makes it impossible to measure all lenses in a null configuration without expensive components for dynamic null testing.¹⁸ Aspheric surfaces will not be tested in a null configuration, resulting in significant measurement differences. These large departures will generate retrace errors in the measurements. Reverse ray tracing is implemented here to calibrate for retrace errors.^{19,20} An alignment tolerance has been applied in order to determine the baseline accuracy of the system.²¹

The imaging path of the interferometer consists of an afocal relay to image the test part onto the camera. An aperture at the common focus of the two relay lenses serves as an imaging path spatial filter reducing stray light. A polarizer is needed before the camera so that interference can be observed. Phase shifting is achieved with a mirror translated by a piezoelectric transducer.

3 Whole Lens Reconstruction

The described interferometer is capable of providing a whole lens reconstruction by measuring the radius of curvature and the surface profile of both the concave and convex surfaces of a contact lens, as well as the lens thickness. Each radius is determined from the distance moved between the cat's eye and the usual confocal measurements of the surface.^{16,22} Both surfaces are measured from the same side of the contact lens so the distance between the cat's eye measurements can be used to calculate the thickness of the lens.

Refraction at the concave surface will change the apparent cat's eye location of the convex surface; therefore, the measurement of the concave surface is needed for compensation. The confocal measurement of the convex surface is also affected by refraction at the concave surface and must be accounted for. Reverse raytracing uses a model of the interferometer to correct retrace errors from measuring surfaces in a non-null configuration. A measurement of the concave surface of the contact lens can be included in the model to correct for refraction during both the cat's eye and confocal measurements of the convex surface. Tracking the distance moved from each cat's eye measurement allows the location of both surfaces to be known at all times and is included in the reverse raytrace model. In these measurements, values for the index of refraction of the saline and the contact lens are required. As noted earlier, these values can be obtained from separate measurements of the materials. A uniform index for the contact lens is assumed. Custom raytrace software was developed in IDL to perform the reverse raytrace calculations. The software implemented a graphical user interface

Fig. 3 Reference prism and variable saline path assembly.

with live fringe feedback, motorized contact lens position control, and realtime surface reconstruction utilizing the custom raytracing software.¹⁷

The results of these absolute surface measurements are a full three-dimensional (3-D) model, or whole lens reconstruction of the contact lens. The resulting model can be used to simulate the results of other measurements such as transmission testing. Comparison of a transmission measurement simulated from the model to an actual independent transmission measurement will verify that this system not only provides detailed information about the surfaces but can also produce the same information as transmission testing.

4 Coherence Window Stitching

The short coherence length of the source used in LOCOH can make it impossible to capture the full surface in one measurement for some surface shapes. The coherence window can be shifted across the surface under test and stitched with many measurements to develop an optical path difference (OPD) map of the entire surface. The coherence window is shifted by moving the reference surface. The angle of the reference surface changes each time the coherence window is moved since translation stages have some finite wobble. The test surface remains stationary, so the change in tilt can be completely attributed to the reference surface. This is corrected by using regions of overlap between the stitched measurements of the surface. Overlapping regions of consecutive measurements are used to compensate for the piston and tilt of each additional measurement. This results in a full OPD map that far exceeds the coherence length of the source. For example, a surface with 300 μm of OPD usually requires 10 separate measurements to be stitched together.

Large departures result in fringe frequencies that are close to the Nyquist limit of the detector and sometimes cause the unwrapping algorithm to fail. These failures result in 2π ambiguities, which appear as surface features with the height of half a wavelength (325 nm). Averaging multiple measurements with these ambiguities can reduce the appearance of these artifacts. Stitching more measurements will minimize the impact of these unwrapping errors, but these errors can still appear as false features in the surface reconstruction. It is also possible to translate the contact lens relative to the transmission sphere to change the radius of curvature of the test wavefront to match the local slope of the surface within a measurement zone. The change would be done between measurements of a surface and must be accompanied by a compensating motion of the reference prism to maintain coherence. This procedure will reduce the local fringe frequency in a measurement zone and completely eliminate reconstruction errors at the expense of computation. Individual measurement zones are then stitched together. This option has not been implemented to date.

5 Verification of Accuracy

The accuracy of LOCOH was verified by comparing measurements with a commercial interferometer of known accuracy. The measurements were made on a 1.5-mm-thick glass sample with 8-mm concave and 10-mm convex radii of curvature. The shape was selected to simulate a contact lens. Any large differences above the accepted accuracy of the commercial interferometer indicate errors in the LOCOH

measurement. Comparison with the commercial system only verifies the accuracy of measurements near null. System accuracy for large departures is verified through repeatability of decentered sphere measurements. The sphere can be measured near null where the accuracy is known and compared with measurements of the same sphere with decenter to simulate large departures. Any difference between the null measurement and a reconstruction of the same surface with large amounts of decenter indicates error. Both of these tests are used to verify the described interferometer.

5.1 Verification of Accuracy Near Null

The accuracy of the described interferometer is verified by comparison to measurements made with a commercial WYKO 6000 phase-shifting interferometer. The WYKO measurement was made using an $F/0.75$ transmission sphere, which can measure more of the surface than LOCOH can. Over this 10-mm-diameter area, the WYKO interferometer verified that the surface of the part is spherical to better than 15 nm RMS and 40 nm $P - V$. Measurements from LOCOH over a 6.5-mm diameter also showed that the surface was spherical to 15 nm RMS and 40 nm $P - V$.¹⁷ The radius of curvature of the surface measured by LOCOH based upon the cat's eye reflection also matched the commercial interferometer's measurement to 0.063% of the radius, which is high precision for most manufacturing tolerances.²³

5.2 Verification of Accuracy for Large Departures

Comparison of measurements made near the null condition verifies the accuracy for small departure surfaces. The WYKO was used to compare accuracy for small departures since the WYKO is only accurate for null measurements. LOCOH has the advantage of being able to measure freeform shapes with departures of 300 μm from spherical. In order to verify the accuracy for these large departures, a different method is needed. Since the interferometer uses reverse raytracing to reconstruct the surface, the LOCOH system will reconstruct the same surface that was measured at null even if it is decentered. Decenter of the surface will introduce linear OPD, which can be used to test the system in a non-null condition. Repeated reconstruction of the same surface features demonstrates the accuracy of the interferometer when measuring large departures.

Any random surface can be thought of as a superposition of sections of a decentered spherical surface. Measuring a spherical surface at multiple locations that push the limit of the interferometer's dynamic range simulates all of the possible departures and slope errors that may be measured. The error in reconstructing decentered spheres can then be directly applied to the system accuracy for any arbitrary large departure surface.

The measurement of a sphere near null was compared to many measurements of the same sphere at different decentered locations.¹⁷ This was done for two different amounts of departure. For mild departures ($\sim 50\text{-}\mu\text{m}$ PV OPD), the RMS residual error was 35.4 nm ($\lambda/20$) with a maximum error of 178 nm ($\sim \lambda/4$). For large departures ($\sim 350\text{-}\mu\text{m}$ PV OPD), the RMS residual error was 73.1 nm ($\lambda/9$) with a maximum error of less than a wavelength.¹⁷ Without correction, typical retrace errors are 10% of the departure, but the reverse

raytracing applied to the LOCOH measurements corrects the residual error to better than 0.05% of the departure.

5.3 Comparison with Transmission Testing

Measurements made by LOCOH result in a full 3-D absolute model of the lens, or its whole lens reconstruction. This constructed model can be used to simulate other tests, such as a transmission test, assuming uniform index of refraction throughout the lens. Comparison of this simulated transmission test with an actual transmission test demonstrates the accuracy of the whole lens reconstruction, which consists of the two individual surface measurements, the radius of curvature measurements, and the thickness measurement.

A glass calibration lens is used for the comparative measurements. The BK7 glass lens is shaped like a contact lens, with a concave radius of 8 mm, convex radius of 10 mm, and 1.5 mm thickness. The calibration lens has an optical power of about -10 diopters. The actual transmission test was made using a Mach-Zehnder interferometer.²⁴ The whole lens reconstruction from LOCOH measurements along with a model of the Mach-Zehnder interferometer is used to simulate the transmission test. The simulated OPD can be directly compared to the measured transmitted OPD.

The measured and simulated transmission OPDs are shown in Fig. 4. Figure 5 shows the difference between these two measurements. The RMS of the difference is about 17 nm. The residual error is dominated by coma, which could easily be caused by system misalignment that is not captured in the simulated interferometer model. The lenses in the Mach-Zehnder model were assumed to be perfectly aligned.

6 Contact Lens Measurements

To date, the surfaces of several different types of contact lenses have been measured by the LOCOH interferometer. Different lenses have specific surface shapes designed to correct different kinds of refractive errors. Each surface shape poses a different challenge for surface metrology. Surface

Difference Between Simulated and Measured Transmission Maps

Fig. 5 Difference between simulated and measured OPD of a glass sample lens ($x - y$ dimensions are in mm).

measurements along with thickness profiles and power maps associated with the whole lens reconstructions of spherical, toric, and bifocal contact lenses as measured in saline solution are presented here. The ophthalmic power maps^{25,26} are computed according to Eq. (1), where r is the radial location and z is the sag at that location of the transmitted wavefront through the contact lens:

$$\Phi_A = \frac{\frac{\partial z}{\partial r}}{r \sqrt{1 + \left(\frac{\partial z}{\partial r}\right)^2}}. \quad (1)$$

The individual surface measurements are influenced by the mounting of the contact lens. The edge of the lens rests on an annular glass plate. The hole allows the measurement beam to pass through the plate. There are no specifications in

Fig. 4 (a) Measured and (b) simulated OPD at the detector for a transmission test of the calibration lens ($x - y$ dimensions are in mm).

the contact lens design or manufacture that require the edge or rim of the contact lens to be planar. As a result of self-weight deflection, the lens will settle on high points, introducing shape distortions into the surfaces of the contact lens. Fortunately, the same distortion will appear on both surfaces so that the thickness profile and power map of the contact lens are not changed. Any errors in the glass mounting plate would produce similar effects.

6.1 Spherical Lenses

Spherical lenses increase or reduce the refractive power of the cornea to correct for hyperopia or myopia. The lenses have both spherical anterior and posterior surfaces and provide refractive correction of rotationally symmetric power. Spherical surfaces can be measured in the null condition; however, these spherical surfaces are deformed by holding them and are measured to have large departures.

Two spherical lenses are measured here, one made of a hydrogel material and the other of a silicone hydrogel. The first lens shown is the hydrogel lens with a designed power of -2.50 D and an 8.7-mm base radius of curvature. According to ISO standards, the base radius of curvature of a contact lens is determined using only the vertex sag of the concave or posterior surface of the lens and the full diameter of the lens. In order to show the features on the surface, the measured surfaces have their base spheres removed. The surfaces that were measured for the hydrogel spherical lens are shown in Fig. 6. The measured radii of curvature of the concave and convex surfaces are 8.775 and 9.399 mm, respectively, over the measurement zone on the lens. The measured radius of the concave surface should not be compared to the stated base radius of curvature of the lens, as the two values are for different areas on the lens.

LOCOH employs stringent stray light mitigation; however, unwanted light still illuminates the center of the detector, reducing fringe modulation and making it difficult to recover surface information. Figures 6–8 have a region without information near the center of the plot for this reason. Regions near the edge are also masked, where large surface slopes cause the fringes to alias. Stitching of more

measurements at different focus positions may reduce this effect and increase the measurement area. Ten measurements were combined for the data shown.

The most prominent feature in the surface maps is astigmatism, likely due to the lens mounting and self-deflection. The surface features are highlighted by removing some Zernike terms. Figure 7 shows the same surfaces but with the first nine Zernike terms removed. These nine Zernike terms are the terms up to the fourth order. The region shown has also been cropped so that a unit circle could be used for the fit. These figures show that the surfaces are fairly smooth but have some residual astigmatism and trefoil that appear on both surfaces. These features, along with the low-order terms masked by the removal of the Zernike terms, will cancel out in the thickness profile computed from the whole lens reconstruction, indicating that the overall lens is deformed.

The whole lens reconstruction results in a thickness profile of the lens that can be used to calculate a transmitted wavefront or even simulate the performance of the lens on the eye. Figure 8 shows the thickness profile and a power map calculated from the transmitted wavefront. The minimum thickness of this negative lens is $113\text{ }\mu\text{m}$; however, this minimum is displaced from the center of the map, indicating that the lens was decentered from the optical axis of the interferometer. The power map in Fig. 8 was centered and cropped relative to the location of the measured center and matches the design power of -2.50 D. The thickness profile shows the same missing data as the surface maps, but the power map has new data masked at the center. This is because the equation for axial power divides by both r and dr/dz . When either of these is zero, the axial power (Φ_A) blows up. These regions are masked to give better contrast to the rest of the figure.

The second spherical lens measured is made of a silicone hydrogel. This lens has a designed power of -3.00 D and an 8.7-mm base radius of curvature. The residual features after removal of the base sphere for both surfaces of the lens are shown in Fig. 9. The measured radii of curvature over the measurement zone are 8.848 and 9.468 mm. Common surface distortions appear on both surfaces. A more interesting

Fig. 6 Hydrogel spherical lens surface maps ($x - y$ dimensions are in mm). (a) Concave, departure from 8.775-mm sphere and (b) convex, departure from 9.399-mm sphere.

Fig. 7 Hydrogel spherical lens with nine Zernike terms removed ($x - y$ dimensions are in mm). (a) Concave surface and (b) convex surface.

Fig. 8 Hydrogel spherical lens (a) thickness and (b) power maps ($x - y$ dimensions are in mm).

feature is the fourth-order buckling that appears on both surfaces that is unlikely to be related to mounting and may be a characteristic of silicone hydrogel lenses or may be related to the temperature or salinity of the solution.

Figure 10 shows the thickness profile of the lens along with its power map. The thickness profile for this lens shows a center thickness of $71 \mu\text{m}$ with good centration, indicating that it was aligned to the interferometer's axis during measurement. The calculated power map shows that the power of the lens is close to the designed power but shows some central astigmatism.

6.2 Toric Lenses

Toric lenses provide correction to the base refractive power of the cornea as well as cylinder power to correct for astigmatism. At least one surface of the contact lens must have a toric shape to do this. The ability to measure toric surfaces

was already demonstrated on the spherical lenses of the previous section. A toric contact lens will have different amounts of toricity on the two surfaces, resulting in a reconstructed thickness profile that shows the nonrotationally symmetric astigmatic correction.

The toric lens shown in the following measurements is made of hydrogel and has a base refractive correction of -3.00 D , a cylinder of -1.75 D , and an 8.7-mm base radius of curvature. The measured surfaces relative to best-fit base spheres are shown in Fig. 11. Removal of nine Zernike terms will eliminate the low-frequency features that dominate Fig. 11 and highlight the high-frequency surface features. Figure 12 shows the same two surfaces with the same base sphere and nine Zernike terms removed. The two surfaces still show similar features, which indicates a variation of the lens.

Most of the features on both surfaces appear the same, but the thickness profile and power map show that the surfaces

Fig. 9 Silicone hydrogel spherical lens surface maps ($x - y$ dimensions are in mm). (a) Concave, departure from 8.848-mm sphere and (b) convex, departure from 9.468-mm sphere.

Fig. 10 Silicone hydrogel (a) thickness and (b) power maps ($x - y$ dimensions are in mm).

Fig. 11 Hydrogel toric lens surface maps ($x - y$ dimensions are in mm). (a) Concave, departure from 7.979-mm sphere and (b) convex, departure from 8.566-mm sphere.

Fig. 12 Hydrogel toric lens with nine Zernike terms removed ($x - y$ dimensions are in mm). (a) Concave surface and (b) convex surface.

do not have the same amount of astigmatism. The residual between them is the designed cylinder power. Figure 13 shows the thickness profile and power map obtained from the whole lens reconstruction. The thickness profile clearly has an elliptical shape, indicating that the lens measured was toric. The power map has the typical bowtie pattern of astigmatism with the base power of -3.00 D just slightly counter-clockwise from vertical. Near horizontal, the cylinder power of -1.75 D is added to the base power to give nearly -4.75 D. This is the prescription given in the usual ophthalmic fashion, where the cylinder power is a complete add to a base power for the lens. This is in opposition to the usual medial focus definition of best fit used in aberration analysis.

6.3 Bifocal Lenses

Bifocal lenses have some of the more interesting surface shapes to measure. At least one surface of the lens contains

a series of discrete, annular zones of different radii of curvature that alternate between distance and near power corrections. The lens measured here has multizone features on the posterior surface, or the concave surface, as it is referred to here. This means that the second surface needs to be measured through the surface with a complicated structure.

The selected lens is a hydrogel with $+4.00 / +2.00$ D of power and a base radius of 8.5 mm. The dual powers listed in the prescription mean that some annular regions of the lens will have $+4.00$ D and others will have $+2.00$ D. The surfaces measured by the presented interferometer are shown in Fig. 14. The annular regions are clearly visible on the concave surface and are not apparent on the convex surface. The convex surface is actually less variable than the spherical lens surfaces shown in Figs. 6–10, with $P - V$ features of $3.5 \mu\text{m}$ compared to the 50 and $30 \mu\text{m}$ features of the hydrogel and silicone hydrogel lenses.

Fig. 13 Hydrogel toric lens (a) thickness and (b) power maps ($x - y$ dimensions are in mm).

Fig. 14 Bifocal lens surface maps ($x - y$ dimensions are in mm). (a) Concave, departure from 8.595-mm sphere and (b) convex, departure from 7.952-mm sphere.

The removal of nine Zernike terms in Fig. 15 shows the different annular regions on the concave surface but highlights a threefold deformation symmetry. The convex surface is nearly spherical but shows the same threefold rotational symmetry. This, again, is from a three-point contact with the mounting surface, but the effect is much smaller than seen earlier, likely because the lens is thicker, with a center thickness of $190 \mu\text{m}$. The thickness profile and power map can be calculated for the lens in the same way as the spherical and toric lenses and are shown in Fig. 16.

The thickness profile looks like the profile of a spherical lens since its shape is dominated by its base spherical power. The multizone features, however, are clearly visible in the power map of the lens.

6.4 Contact Lens Transmission Testing

As a demonstration of the LOCOH system, the transmitted wavefront generated from the whole lens reconstruction

model of a contact lens has been compared to an actual measurement of the same contact lens by a Mach-Zehnder interferometer. The demonstration used the spherical silicone hydrogel contact lens with a power of -3.00 D and a base radius of 8.7 mm , as previously shown in Figs. 9 and 10. The surfaces of the contact lens exhibit features much larger than the calibration lens shown in Sec. 5.3. The calibration lens had an RMS departure from spherical of 10 nm , while contact lenses show RMS departures from spherical of $5 \mu\text{m}$. The whole lens reconstruction of the contact lens was used to simulate a transmission OPD. Both the actual measured transmission map and the simulated transmission map are shown in Fig. 17. The difference between these two independent measurements of the transmitted wavefront of the contact lens is shown in Fig. 18. The result is an RMS difference of 36.26 nm , or about $\lambda/18$ of the measurement wavelength (or about $\lambda/15$ at the peak of the photopic response curve). Excellent agreement has been achieved. The residual differences could be due to a number of factors including a

Fig. 15 Bifocal lens surface maps with nine Zernike terms removed ($x - y$ dimensions are in mm). (a) Concave surface and (b) convex surface.

Fig. 16 Bifocal lens (a) thickness and (b) power maps ($x - y$ dimensions are in mm).

Fig. 17 (a) Measured and (b) simulated OPD ($x - y$ dimensions are in mm).

spatial variation of the index not included in the whole lens reconstruction model or changes in mounting between the LOCOH and the transmission measurement.

The comparison in Fig. 18 indicates larger differences than the comparison measurements made with the calibration lens, as shown in Fig. 5. There are two major differences between the calibration lens and the contact lens measured. The calibration lens is made of N-BK7 and has index of refraction variation throughout the lens that is much smaller than what can be resolved here. Also, the lens is rigid and will not change between measurements in LOCOH and measurements in the Mach-Zehnder. The contact lens will change its shape and index of refraction properties depending on temperature, solution salinity, and mounting conditions in the cuvette.

The 36-nm features shown in the difference map could correspond to a 0.0004 index of refraction variation in a 100- μm -thick contact lens. If the lens can be mounted the same way between measurements in LOCOH and a transmission test, then it may be possible to determine index of refraction variations in a contact lens on this scale.

Fig. 18 Difference between the measured and simulated OPDs of a soft contact lens ($x - y$ dimensions are in mm).

7 Discussion and Conclusions

An interferometer capable of measuring contact lenses submerged in solution is presented here along with a verification of its accuracy. Both surfaces of the contact lens are measured in a single operation, and the system reports the surface figure of the two surfaces, the radii of curvature of the surfaces, and the thickness of the contact lens. The convex anterior surface of the contact lens is measured through the concave posterior surface. The resulting data can be used to produce a whole lens reconstruction model or complete 3-D model of the lens. The model can be used, assuming a uniform index of refraction of the lens material, to compute a predicted power map that can then be compared to the lens prescription. The measurements made here match very closely with the lens designs and can be used to identify manufacturing differences in contact lenses.

Measurement of both surfaces also allows features in the thickness and features on the surfaces to be separated. A lens may be measured to have the correct thickness profile and predicted power map, but the shape of the surfaces indicates lens deformation. This is important since transmission testing provides information about the thickness profile of the lens but not surface deformations. Contact lens deformations may cause discomfort or poor vision that would not be identified by a transmission test.

The interferometer was designed to overcome the particular issues of measuring multiple highly deformed low-reflectivity surfaces in close proximity. Low-coherence interferometry is used to isolate the surface measurements. Stray light management and dispersion compensation produces fringe patterns with enough modulation to determine the OPD at the detector. The errors from measuring surfaces with large departures from null are corrected with reverse raytracing.

The accuracy of reconstruction depends on both the reverse raytracing algorithms and how well the real interferometer matches the model used for tracing the rays. The accuracy was verified by measuring surfaces near null on a commercial system and comparing them to measurements made by this interferometer. Near null, the system demonstrates accuracies to $\lambda/20$ RMS. Large departures were also verified by measuring the same surface with different amounts of slope and sag error. The measurements demonstrated accuracies of $\lambda/9$ RMS.

Several contact lens measurements were presented. The surface measurements indicate lens deformations, which are combined to produce a whole lens reconstruction and calculated thickness profiles and power maps. A simulated OPD map for a contact lens was compared to an independent transmission measurement of the same contact lens. Excellent agreement was found to be within 36.26 nm or $\lambda/18$ of the measurement wavelength.

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References

1. R. M. Pearson and B. J. W. Evans, "A comparison of in-air and in-saline focimeter measurement of the back vertex power of spherical soft contact lenses," *Ophthalmic Physiol. Opt.* **32**(6), 508–517 (2012).
2. R. M. Pearson, "Aspects of wet cell measurement of back vertex power of contact lenses," *Clin. Exp. Optom.* **91**(5), 461–468 (2008).
3. L. R. Wang, J. Y. Zhang, and Z. Ya, "Calibration error on the measurement of back vertex power for contact lenses with method using focimeter with manual focusing," *Optom. Vis. Sci.* **79**(2), 126–133 (2002).
4. P. E. Murphy et al., "Subaperture stitching interferometry for testing mild aspheres," *Proc. SPIE* **6293**, 62930J (2006).
5. G. A. Williby et al., "Interferometric testing of soft contact lenses," *Proc. SPIE* **5180**, 329–339 (2003).
6. K. Seong and J. E. Greivenkamp, "Surface reconstruction based on transmission interferometric testing," *Proc. SPIE* **6671**, 66710M (2007).
7. K. Seong, "Optical metrology for transmission interferometric testing," PhD Dissertation, University of Arizona (2007).
8. G. A. Williby, "Transmitted wavefront testing of complex optics," PhD Dissertation, University of Arizona (2003).
9. B. M. Pixton and J. E. Greivenkamp, "Automated measurement of the refractive index of fluids," *Appl. Opt.* **47**, 1504–1509 (2008).
10. E. P. Goodwin et al., "Dual interferometer system for measuring index of refraction," in *Optical Fabrication and Testing*, OSA, Washington, DC (2006).
11. E. P. Goodwin, "Dual interferometer for measuring index of refraction," PhD Dissertation, University of Arizona (2007).
12. I. Verrier, C. Veillas, and T. Lépine, "Low coherence interferometry for central thickness measurement of rigid and soft contact lenses," *Opt. Express* **17**(11), 9157–9170 (2009).
13. I. Verrier, C. Veillas, and T. Lépine, "Influence of interfaces reflectivity for central thickness measurement of a contact lens by low coherence interferometry," *J. Eur. Opt. Soc.* **13006**, 6–9 (2013).
14. K. Creath and J. C. Wyant, "Measurement of spherical surfaces," *Proc. SPIE* **1332**, 2–7 (1991).
15. T. Schmitz, "Uncertainties in interferometric measurements of radius of curvature," *Proc. SPIE* **4451**(704), 432–447 (2001).
16. L. A. Selberg, "Radius measurement by interferometry," *Opt. Eng.* **31**(9), 1961 (1992).
17. K. C. Heideman, "Surface metrology of contact lenses in saline," PhD Dissertation, University of Arizona (2014).
18. J. H. Burge, "Applications of computer-generated holograms for interferometric measurement of large aspheric optics," *Proc. SPIE* **2576**, 258–269 (1995).
19. J. E. Greivenkamp, "Design and calibration of large dynamic range optical metrology systems," *Proc. SPIE* **6024**, 602403 (2005).
20. D. Liu et al., "Non-null interferometric aspheric testing with partial null lens and reverse optimization Dong," *Proc. SPIE* **7426**, 74260M (2009).
21. K. C. Heideman and J. E. Greivenkamp, "Effect of alignment and tolerances on reverse raytrace calibration," *Proc. SPIE* **9203**, 92030H (2015).
22. C. Zhao, "Measuring the radius of curvature of a spherical mirror with an interferometer and a laser tracker," *Opt. Eng.* **44**(9), 090506 (2005).
23. H. H. Karow, *Fabrication Methods for Precision Optics*, pp. xiv, John Wiley & Sons, New York (1993).
24. J. E. Greivenkamp et al., "Interferometry and ophthalmics at the college of optical sciences," *Proc. SPIE* **9186**, 91860W (2014).
25. J. Schwiegerling, "Visual Optics," in OPTI 435/535 course notes, College of Optical Sciences, University of Arizona (2013).
26. J. Schwiegerling, *Field Guide to Visual and Ophthalmic Optics*, p. 44, SPIE Press, Bellingham, Washington (2004).

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