Precision interferometric measurements of refractive index of polymers in air and liquid

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ABSTRACT

We have developed a procedure for precise measurement of the group refractive index for materials in air and liquid environments, using a low coherence interferometer. For example, in manufacturing of soft contact lenses, the lenses are always kept hydrated in a saline solution. Knowing accurate refractive index of the lens is important to metrology and quality control purposes. The small refractive index difference between the liquid and the lens makes such tasks especially challenging. The developed procedure allows us to obtain measurement repeatability for group refractive index less than 1 x 10^{-3} for materials with thicknesses on the order of 100 microns, when measured in liquid. The measurement repeatability further improves for measurements in air, or for thicker materials.

Keywords: refractive index, low-coherence interferometry, metrology

1. INTRODUCTION

The refractive index of a lens is an important parameter in lens design. When designing a lens to have a specific refractive power, the index of refraction of the material affects the thickness and curvature of the lens. Lens thickness is an extremely important parameter in the design of contact lenses and intraocular lenses. The standard method of measuring the index of refraction of contact lenses is a contact method using an Abbe refractometer and is described in ISO 18369-4[1].

Recently, non-contact metrology methods have become increasingly popular in the field of industrial production of various devices. Most of these methods rely on optical properties of the material measured. For example, the OptiGauge™ uses fast low-coherence interferometry to precisely measure optical thickness of the materials of interest. In order to determine the physical thickness of the material with low-coherence interferometry, the refractive index of the material needs to be known. Precise knowledge of the refractive index is essential to obtain precise thickness of the materials. Since the index of refraction of many plastic materials tend to change batch to batch, and is also a function of temperature and wavelength, the index of refraction needs to be measured accurately in order to properly certify the physical thickness of the material.

2. INSTRUMENTATION

Index of refraction measurements were performed using a commercially available dual low-coherence all-fiber interferometer (OptiGauge™, Lumetrics, Inc.), a schematic of which is shown in Figure 1. Low coherence light from a superluminescent light emitting diode (SLED), having a center wavelength of 1310 nm and a bandwidth of about 50 nm, passes through Port 1 and Port 2 of an optical circulator into a sample fiber. The light from the sample fiber passes through an optical probe and is focused on the sample. Light reflecting off of each optical interface in the sample passes back through the optical probe, back through the sample fiber, back through Port 2, and passes through Port 3 of the circulator into an all-fiber dual Michelson interferometer. Light from a 1552 nm laser diode is added into the optical path of the low-coherence light via wavelength division multiplexer WDM 1. The combined laser and low coherence light passes through a 50/50 fiber coupler and is split into two beams. Each beam passes through a PZT fiber stretcher, and is reflected back by a Faraday rotator mirror.

During operation, voltage waveforms are applied to the pair of PZT fiber stretchers, 180^{o} out of phase with each other. The voltage alternately changes the path lengths of the pair of fiber stretchers in a push-pull configuration. The 2 beams of light at each wavelength, reflected from the Faraday Mirrors, interfere with each other as they are recombined at the

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50/50 coupler. The combined light is passed through a second wavelength division multiplexer (WDM 2) where it is separated into individual interfering beams, at 1552 and 1310 nm respectively. The beams are then sent to respective photodiodes, which convert the interference signals to voltage levels as a function of time.

The 1310 nm interfering light passes through a 1310 nm photodiode and is pre-processed before A-D conversion. The 1552 laser interferometer signal is sent to a zero-crossing detector, which is used to provide a uniform distance scale clock for acquiring the low coherence 1310 nm interference signal. The laser clock signal is used to trigger the A-D conversion of the low coherence interference signal, ensuring that data is collected at constant distance intervals. Further details of the operation of the interferometer and its performance can be found in reference 2.

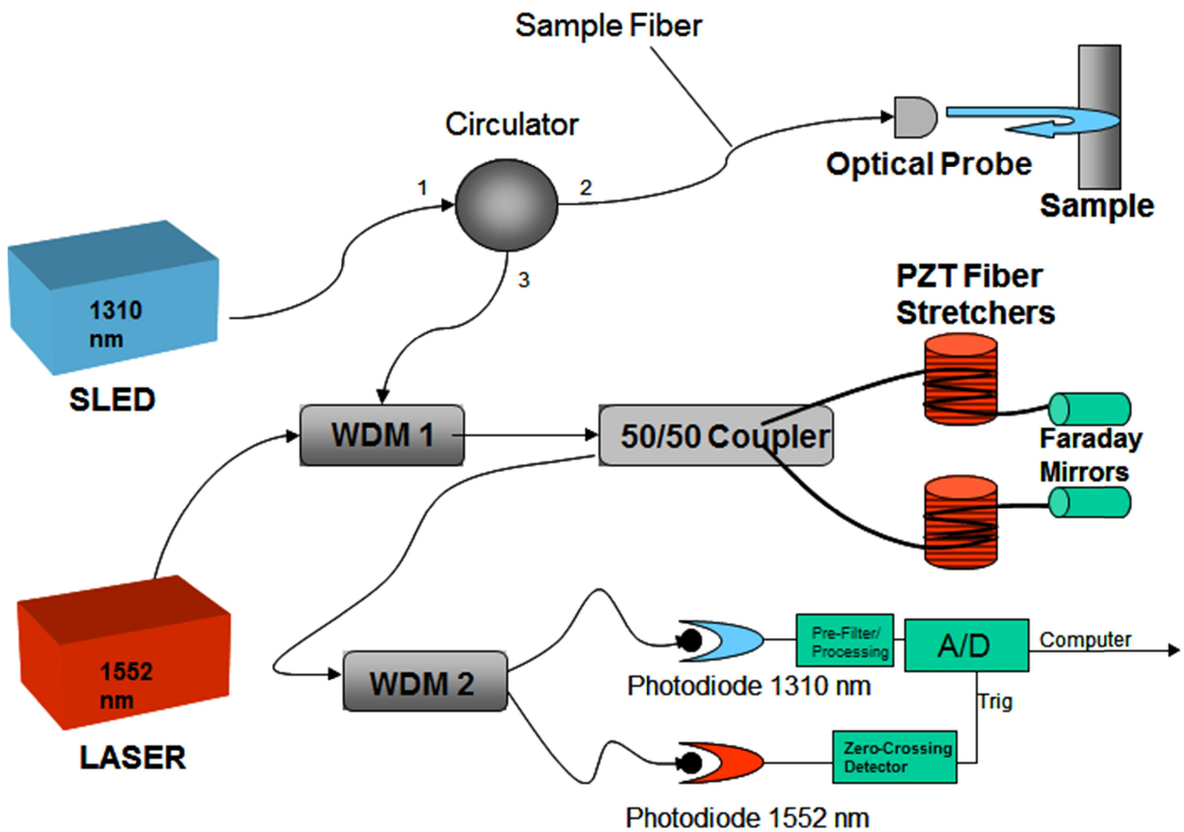

Figure 1. Schematic of the dual low coherence interferometer used in the experiments.

3. INDEX OF REFRACTION MEASUREMENT PROCEDURE

3.1 Index of Refraction Measurements in Solution

The main principle behind the refractive index measurement is based on measuring the change in the optical distances between two fixed interfaces when material of interest in inserted into the gap between these interfaces. The low-coherence interferometer in OptiGauge^{TM} is perfectly suitable for this task.

To demonstrate the measurement procedure, we use a soft contact lens placed into a saline solution within a glass cuvette. The measurement procedure allows measuring of the refractive indices of the saline solution, of the contact lens, as well as actual physical thickness of the contact lens. Since the measurement procedure involves multiple consecutive measurements, it is important to ensure that the physical distance between the glass interfaces of the cuvette do not change. Therefore, it is important to ensure that the cuvette does not shift its position between measurements, and the temperature of the solution in the cuvette is kept constant.

Details of the measurement configuration and procedure are illustrated in Figure 2. The left region of Figure 2 (Section A) shows a schematic of a cuvette and indicates the measured distances during each measurement step. Section B lists the measured optical distances during each step, as product of physical thickness and the respective refractive index. Section C shows the image of the actual setup, which contains the glass cuvette and an optical probe with 50 mm focal length. A thermocouple (not shown) is inserted into the cuvette before each measurement to record the temperature, and to ensure that the temperature of the solution remains within 0.1 ^{o}C during the measurements.

The procedure contains 3 steps:

Step 1: Measure the optical thickness of the lens in a solution inside the cuvette.
Step 2: Measure the optical distance between the cuvette walls, with only the saline solution present.
Step 3: Measure the optical distance between the cuvette walls without the saline solution present.

During Step 1, the cuvette is filled with the saline solution. The contact lens is placed inside a cuvette, with its convex surface facing upward (Figure 2A-Step1). The cuvette is placed on the measurement platform, approximately centered below the measurement optical probe. It is important to fixate the location of the cuvette with respect to the probe, so the cuvette does not shift between the measurement steps. Typically, a double sticky tape can be used for fixating the cuvette. Before taking the first set of measurements, a small thermocouple is also placed inside the cuvette to monitor the temperature of the solution and lens during measurement.

The measurement platform includes a manual xy stage, which is used to position the apex of the lens under the low-coherence measurement beam. The amplitude of the interferometric signal can be used to precisely position the lens. When the apex of the lens is located directly under the measurement beam, the beam is crossing the surface of the lens at a right angle, thus directing the reflections directly back into the optical probe, and maximizing the amount of the reflected light that is analyzed by the interferometer.

Figure 3 shows a section of the OptiGauge™ software measurement screen, which corresponds to the configuration shown in Figure 2A Step1, when the apex of the lens is properly positioned under the measurement beam. The graph shows the measured optical intensity of the interferometer peaks as a function of optical distance. Peaks 1-4 correspond to the top inner surface of the cuvette, the top surface of the lens, the bottom surface of the lens and the inner surface of the cuvette's bottom respectively.

Differences in locations between the optical surfaces define the measured optical thicknesses. The distance between peaks 1 and 2 defines the optical distance between the top surface of the cuvette and the top surface of the lens, ($n_s d_2$), where n_s is the refractive index of the solution, and d_2 is the corresponding physical distance. The distance between peaks 2 and 3 defines the optical distance ($n_l t_l$), where n_l is the refractive index of the lens, and t_l is the thickness of the lens. The distance between peaks 3 and 4 defines the optical distance ($n_s d_1$), where n_s is the solution index of refraction and d_1 is the distance between the back side of the lens and the top surface of the cuvette bottom. All three measured optical distances, ($n_l t_l$),($n_s d_1$) and ($n_s d_2$) are important for the refractive index measurement procedure.

In Step 2, the lens is carefully moved away from the measurement beam, without changing the position of the measurement beam location on the cuvette. Only two signal peaks are present in the OptiGauge™ software screen in this configuration. The peaks correspond to the inner surfaces of the cuvette. During Step 2, we measure the optical distance between the surfaces of the cuvette, ($n_s d_o$), where d_o is the physical distance between the top and bottom inner surfaces of the cuvette. In the calculations described below, all the measured distances are referenced to the physical distance d_o which must be kept constant over the course of the three Step measurement process.

The thermocouple is kept in the solution and monitored to make sure that the temperature remains constant to 0.1 ^{o}C with respect to the measurements performed during step 1. The refractive index of water (and thus saline solution) is a strong function of temperature[3,4]. The index of refraction is found to decrease with increasing temperature, and for 1300 nm light it varies by -8.2x10^{-5}/^{o}C at 20 ^{o}C to -1.1x10^{-4}/^{o}C at 30 ^{o}C. In case of a 5 mm cuvette, a 1 ^{o}C temperature change between measurement steps will result in a 0.4 µm error in calculating the physical path length d_o of the cuvette when measured at 20 °C and a 0.55 µm error when measured at 30 °C. Thus measuring at constant temperature is extremely important.

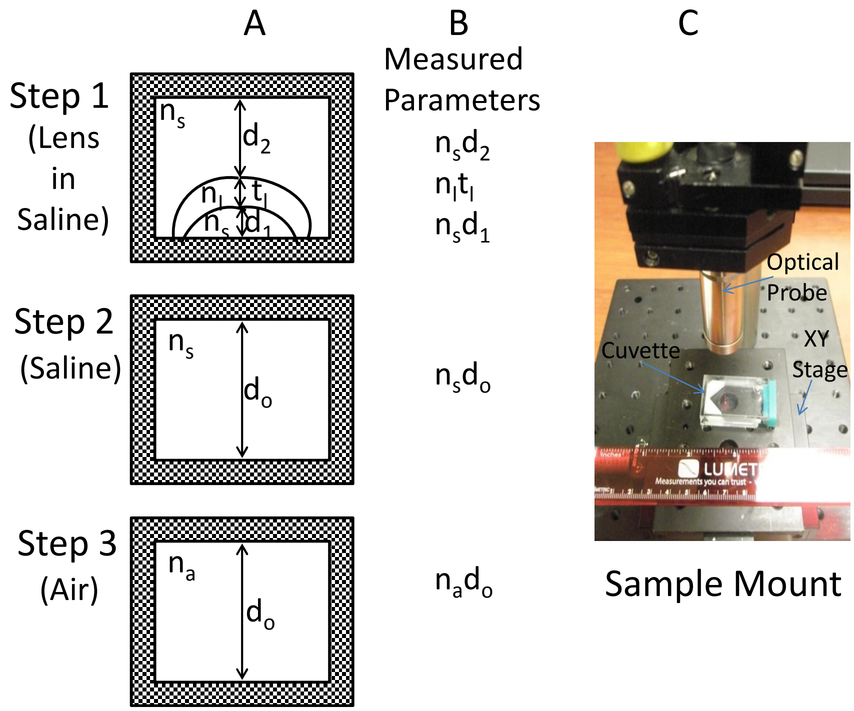

Figure 2. Schematic of the 3 step measurement process, the parameters measured and an image of the cuvette and optical probe used in the measurements.

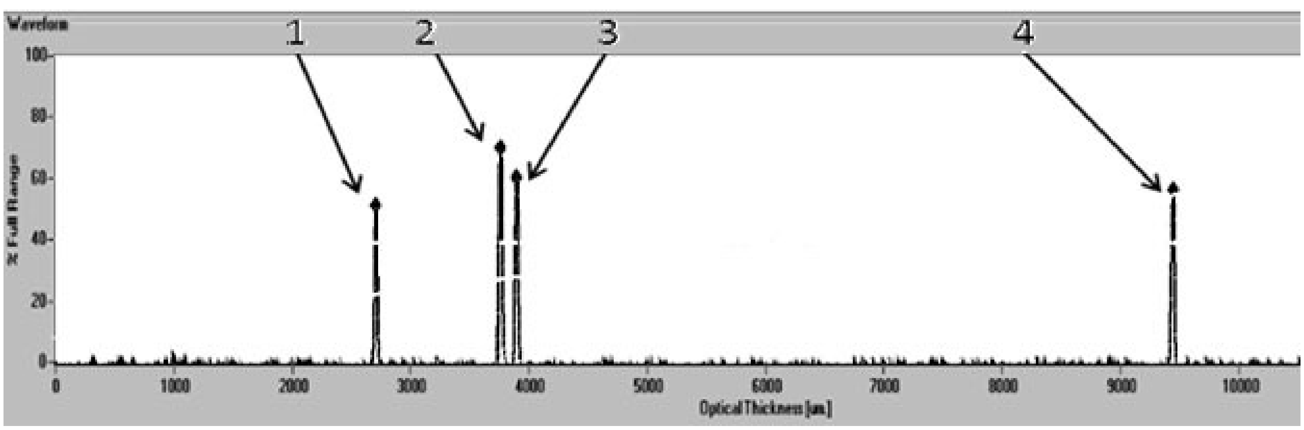

Figure 3. Interferometer scan screen during step 1.

In Step 3 the solution is carefully pumped out from the cuvette using a syringe, and the cuvette is carefully dried with cloth, making sure that the measurement beam remains in the same location of the cuvette. The measured parameter during this step is (n_ad_o), where n_a is the group refractive index of air at the measurement wavelength. The refractive index of air has been extensively studied[5,6] and is a weak function of temperature. The n_a also depends on atmospheric pressure, humidity and CO2 concentration, but this dependence is much weaker than the temperature dependence, and it is ignored for the purposes of this paper.

The refractive index of air is 1.0002684 at 20 °C and 1.0002637 at 25 °C, and the change with temperature is -9.43×10^{-7}/°C at 20 °C and -9.22×10^{-7}/°C at 25 °C. For a 5 mm physical path length cuvette measured in air, a 1 °C temperature change will result in a 4.7 nm error in the calculation of the physical path length d_o of the cuvette when measured at 20 °C, and a 4.6 nm error when measured at 25 °C. Since the measurement error of the cuvette's physical thickness in air is 2 orders of magnitude smaller than when measured in solution, for given temperature change, we assume a constant refractive index of air at 20 °C for all calculations below.

The relationships used to calculate the lens index of refraction are as follows. First, the cuvette optical path d_o is calculated using the relationship

$$d_o = \frac{(n_a d_o)}{n_a}, \tag{1}$$

where $(n_a d_o)$ is the measured parameter during Step 3, and n_a is the index of refraction of air, which is considered to be a constant and equal to 1.000268. The refractive index n_s of solution is then calculated using the relationship

$$n_s = \frac{(n_s d_o)}{d_o}, \tag{2}$$

where $(n_s d_o)$ is the measured parameter during Step 2, and d_o is the value calculated using Equation 1. The lens physical thickness t_l is calculated from the relationship

$$t_l = d_o - \frac{(n_s d_1) + (n_s d_2)}{n_s}, \tag{3}$$

where $(n_s d_1)$ and $(n_s d_2)$ are obtained during Step 1, and n_s is the value calculated in Equation 2. The index of refraction of the lens is calculated from the relationship

$$n_l = \frac{(n_l t_l)}{t_l}, \tag{4}$$

where $(n_l t_l)$ is measured during Step 1, and t_l is the value calculated in Equation 3.

3.2 Index of Refraction Measurements in Air

When measurements are performed in air, the same type of measurement procedure is performed, but Step 2 is eliminated. During Step 1, the lens is inserted into an empty cell (cuvette), that contains a pair of optical flats (walls) separated by a fixed distance. The measurement screen looks similar to that in Figure 3, but the distance between peaks 1 and 2 defines the optical distance $(n_a d_2)$, the distance between peaks 2 and 3 defines the optical distance $(n_l t_l)$ and the distance between peaks 3 and 4 defines the optical distance $(n_a d_1)$. The lens is then removed from the cell and the distance $(n_a d_o)$ is measured as in Step 3 above. Equation 1 is used as to calculate the physical thickness d_o. The lens physical thickness t_l is now calculated using the relationship

$$t_l = d_o - \frac{(n_a d_1) + (n_a d_2)}{n_a} \tag{5}$$

The index of refraction of the lens n_l is then calculated using equation 4 as discussed above.

4. RESULTS AND DISCUSSION

4.1 Soft Contact Lens Measurements in Solution

For the measurements in this paper, the low coherence interferometer is set to 50 Hz measurement rate. In order to ensure high measurement precision of the data, the optical thickness measurements in each step are averaged for 3 seconds (or 150 measurements), and the average values and statistics are saved to a comma-separated file. A set of 10 repeat measurements are performed at each measurement step, before moving on to the next measurement step.

Table 1 shows an example data file showing the time of the measurement in the 1st column, the average optical thickness of the first layer in the 2nd column, the standard deviation of the first layer optical thickness in the 3rd column, the average optical thickness of the lens ($n_l t_l$) in the 4th column, the standard deviation of the lens optical thickness ($n_l t_l$) in the 5th column, the average optical thickness of the bottom gap ($n_s d_1$) in the 6th column and its standard deviation in the 7th column. The optical thickness displayed in column 2, corresponds to the top gap ($n_s d_2$) during Step 1, the solution optical path ($n_s d_o$) during Step 2 and the air optical path ($n_a d_o$) during Step 3. All distance and thickness data in this and other tables is shown in microns.

The data file is analyzed to calculate the lens index of refraction as follows. The mean values of the 10 repeat measurements are first calculated for each of the 5 measured parameters. Table 2 shows a summary of the measured optical parameters and calculated physical parameters obtained from the data shown in Table 1. Columns 2 and 3 show the mean value and the standard deviation of the measured optical parameters shown in column 1. Column 5 shows the calculated values for the physical parameters shown in Column 4. Equations 1-4 are used in the calculations.

Table 1. Soft contact lens measurement sequence 575-075-3DCC .

Time	L1	std L1	$(n_l t_l)$	std$(n_l t_l)$	$(n_s d_1)$	std$(n_s d_1)$	
5:25:20 PM	1099.64	0.04	136.41	0.04	5538.40	0.03	
5:25:23 PM	1099.64	0.04	136.40	0.04	5538.40	0.03	
5:25:26 PM	1099.66	0.04	136.40	0.04	5538.40	0.04	
5:25:29 PM	1099.65	0.04	136.40	0.05	5538.40	0.04	
5:25:32 PM	1099.68	0.05	136.41	0.04	5538.39	0.03	Step 1
5:25:35 PM	1099.68	0.06	136.41	0.03	5538.39	0.04	
5:25:38 PM	1099.69	0.04	136.41	0.04	5538.37	0.04	
5:25:41 PM	1099.71	0.04	136.40	0.04	5538.37	0.04	
5:25:44 PM	1099.71	0.04	136.41	0.04	5538.35	0.04	
5:25:47 PM	1099.75	0.03	136.39	0.04	5538.34	0.04	
5:26:26 PM	6768.26	0.03					
5:26:29 PM	6768.26	0.03					
5:26:32 PM	6768.26	0.03					
5:26:35 PM	6768.27	0.04					
5:26:38 PM	6768.27	0.04					Step 2
5:26:41 PM	6768.27	0.03					
5:26:44 PM	6768.27	0.03					
5:26:47 PM	6768.27	0.02					
5:26:50 PM	6768.28	0.03					
5:26:53 PM	6768.28	0.03					
5:29:16 PM	5033.37	0.05					
5:29:19 PM	5033.39	0.04					
5:29:22 PM	5033.36	0.05					
5:29:25 PM	5033.37	0.04					
5:29:28 PM	5033.39	0.05					Step 3
5:29:31 PM	5033.37	0.05					
5:29:34 PM	5033.37	0.05					
5:29:37 PM	5033.36	0.04					
5:29:40 PM	5033.34	0.05					
5:29:43 PM	5033.34	0.05					

A measurement repeatability study was performed on three different etafilcon A soft contact lenses having three different optical powers. The lenses 575-075 has -5.75 D spherical power and -0.75 D cylinder power, lens 025-125 has -0.25 D spherical power and -1.25 D cylinder power, and lens 600 has 6.00 D spherical power. Each measurement consisted of performing the 3-Step procedure described with reference to Figure 2.

Table 2. Calculations performed on the data in Table 1 for measurement sequence 575-075-3DCC

measured optical parameter	mean optical thickness	measured standard deviation	calculated physical parameter	physical parameter value
$n_s d_2$	1099.681	0.035	d_o	5032.017
$n_l t_l$	136.404	0.007	n_s	1.34504
$n_s d_1$	5538.381	0.022	t_l	96.805
$n_s d_o$	6768.269	0.007	n_l	1.40906
$n_a d_o$	5033.366	0.017		

Tables 3-5 summarize the data obtained on each of the three respective lenses. Each row in the data was obtained using the measurement procedure and the calculation sequence described above with respect to Tables 1 and 2. The average temperature during steps 1 and 2 was recorded during each measurement. The data in Tables 1 and 2 corresponds to the data shown in row 4 of Table 3.

Each lens was measured by 4 different operators at different times of the day. The 1st column of Tables 3-5 show the lens ID along with the operators name and a numerical prefix indicating how many measurements were made by that operator. The 2nd and 3rd columns of Tables 3-5 show the date and time at which the measurements were made. The 4th column shows the calculated index of refraction of the lens n_l during the measurement, the 5th column shows the average temperature during Step 1 of the measurement procedure, and the 6th column shows the standard deviation of the lens index measurement. The 7th column shows the calculated solution index of refraction n_s during the measurement, the 8th column shows the average temperature during Step 2 of the measurement procedure, and the 9th column shows the standard deviation of the solution index measurement. The 10th column shows the calculated lens thickness t_l and the 11th column is the standard deviation of the measured thickness. The data obtained on 7/23/2013 was measured using a different OptiGauge™ interferometer than the other measurements, and with a new batch of solution which had a slightly lower refractive index than the previous batch of solution.

Table 3. Repeatability study on a lens 575-075.

Lens id / OI	date	time	n_l	Lens °C	n_l stdev	n_s	sol °C	n_s stdev	t_l	t_l stdev
575-075-DCC	5/9/2013	5:10 PM	1.40921	25.9	0.000171	1.34504	26.0	2.11E-06	96.999	0.0127
575-075-2DCC	5/9/2013	5:21 PM	1.40802	26.3	0.000226	1.34501	26.3	3.22E-06	97.003	0.0227
575-075-3DCC	5/9/2013	5:29 PM	1.40906	26.3	0.000163	1.34504	26.3	3.71E-06	96.805	0.0120
575-075-DG	5/9/2013	3:09 PM	1.40878	25.6	0.000166	1.34518	25.6	1.70E-06	97.215	0.0094
575-075-2DG	5/9/2013	3:19 PM	1.40815	25.6	0.000190	1.34517	25.6	2.34E-06	97.049	0.0209
575-075-JJ	5/2/2013	3:05 PM	1.40790	26.7	0.000126	1.34493	26.6	5.77E-06	97.000	0.0098
575-75-MH	7/23/2013	3:40 PM	1.40863	26.3	0.00023	1.34483	26.1	3.91E-06	96.860	0.0193
		average	1.40854			1.34503			96.990	
		stdev	0.00052			0.00012			0.133	
		max	1.40921			1.34518			97.215	
		min	1.40790			1.34483			96.805	
		range	0.00132			0.00035			0.410	

Table 4. Repeatability study on lens 025-125.

Lens id / OI	date	time	n_l	Lens °C	n_l stdev	n_s	sol °C	n_s stdev	t_l	t_l stdev
025-125-DCC	5/9/2013	4:30 PM	1.41018	25.6	0.000165	1.34513	25.6	2.34E-06	121.133	0.0112
025-125-2DCC	5/9/2013	4:41 PM	1.40878	25.6	0.000058	1.34508	25.6	3.70E-06	121.229	0.0123
025-125-3DCC	5/9/2013	4:54 PM	1.41018	25.6	0.000152	1.34505	25.6	2.87E-06	121.100	0.0139
025-125-DG	5/9/2013	1:43 PM	1.40886	24.9	0.000064	1.34535	24.8	2.15E-06	121.418	0.0059
025-125-2DG	5/9/2013	2:41 PM	1.40846	25.6	0.000112	1.34520	25.6	8.35E-06	121.367	0.0142
025-125-3DG	5/9/2013	2:50 PM	1.40776	25.7	0.000130	1.34512	25.7	2.81E-06	121.041	0.0165
025-125-JJ	5/1/2013	2:35 PM	1.40847	26.4	0.000131	1.34522	26.2	2.22E-06	121.292	0.0080
025-125-MH	7/23/2013	2:36 PM	1.40867	26.2	0.000084	1.34476	26.3	2.59E-06	121.208	0.0161
		average	1.40892			1.34511			121.224	
		stdev	0.00085			0.00017			0.131	
		max	1.41018			1.34535			121.418	
		min	1.40776			1.34476			121.041	
		range	0.00243			0.00059			0.376	

Table 5. Repeatability study on lens 600.

Lens id /	date	time	n_l	Lens °C	n_l stdev	n_s	sol °C	n_s stdev	t_l	t_l stdev
600-DCC	5/9/2013	4:00 PM	1.40719	25.9	0.000049	1.34504	25.9	2.15E-06	231.765	0.0212
600-2DCC	5/9/2013	4:09 PM	1.40768	25.9	0.000051	1.34501	25.9	3.66E-06	231.109	0.0124
600-3DCC	5/9/2013	4:19 PM	1.40743	26	0.000069	1.34504	26	2.97E-06	231.128	0.0366
600-DG	5/9/2013	2:06 PM	1.40705	25.5	0.000128	1.34516	25.5	4.46E-06	231.123	0.0290
600-2DG	5/9/2013	2:19 PM	1.40758	25.5	0.000078	1.34522	25.5	4.99E-06	230.976	0.0223
600-3DG	5/9/2013	2:32 PM	1.40740	25.6	0.000054	1.34520	25.6	3.38E-06	231.367	0.0185
600-JJ	5/6/2013	12:40 PM	1.40726	24.8	0.000055	1.34531	24.8	3.59E-06	231.558	0.0086
600-MH	7/24/2013	2:21 PM	1.40713	25.8	0.000080	1.34488	25.9	4.71E-06	231.635	0.0186
		average	1.40734			1.34511			231.333	
		stdev	0.00022			0.00014			0.291	
		max	1.40768			1.34531			231.765	
		min	1.40705			1.34488			230.976	
		range	0.00062			0.00042			0.789	

The lower part of Tables 3- 5 show the statistics for repeatability of n_l, n_s and t_l for each lens over the course of this study, which spanned approximately 80 days. The overall relative standard deviation for thickness t_l is higher than expected, and is higher than the overall relative standard deviations for the refractive indices. The primary reason behind this discrepancy is that during the course of the study the lens was not always measured in the same exact location.

The thickest lens has an average thickness $t_l = 231.333$ µm, and $n_l = 1.40734$ with a standard deviation of 0.00022, whereas the thinnest lens has $t_l = 96.990$ µm and $n_l = 1.40854$ with a standard deviation of 0.00052 µm. The third lens had an average thickness $t_l = 121.224$ µm and $n_l = 1.40892$ with a standard deviation of 0.00085 µm.

4.2 IOL Lens Blank Measurements in Air

Testing in air was also performed on a set of 5.1 to 5.2 mm thick intraocular hydrogel lens (IOL) blanks. These IOL blanks were tested without the lenses being hydrated. A two-step measurement process was performed by first placing the lens in the measurement fixture containing a pair of optical flats and a stationary probe. The lens was then removed and measurements were made of the air gap. As before, a50 Hz measurement rate was used, with a sequence of 10 repeated 3-second averages for each set of measurements. The temperature was also monitored during these experiments and the temperature statistics are included in the data.

Table 6 summarizes the measured refractive index results in these experiments. Each of the 5 lens blanks were measured at 6 different times. Each of the 6 measurement group consisted of three sets (labeled A, D and C) of the two-step measurement procedure described above. The top part of Table 6 shows the test # and the date, followed by the average lens index of refraction of each of the 5 lens blanks investigated in successive columns. Test series 1 and 2 were performed at different times of the day on 7/11/13. The middle part of Table 6 shows the statistics for the measured index of refraction, and the lower part of the Table shows the temperature statistics during the measurement. Test series 4 was performed with a different OptiGauge^{TM} interferometer. No statistically significant variations between the two instruments were observed.

The measured standard deviation of the refractive index for the repeat measurements on all of the tested 5.1 to 5.2 mm IOL lens blanks was ≤ 0.0002. As indicated in the bottom section of Table 6, there was a total temperature variation of 2.2 ^{o}C over the course of these measurements. Figure 4 shows a plot of the measured index of refraction for the IOL lens blanks as a function of the temperature at which they were measured. The Figure indicates a slight temperature dependence of the refractive index, with a slope in the order of -0.00015/^{o}C at 25 ^{o}C.

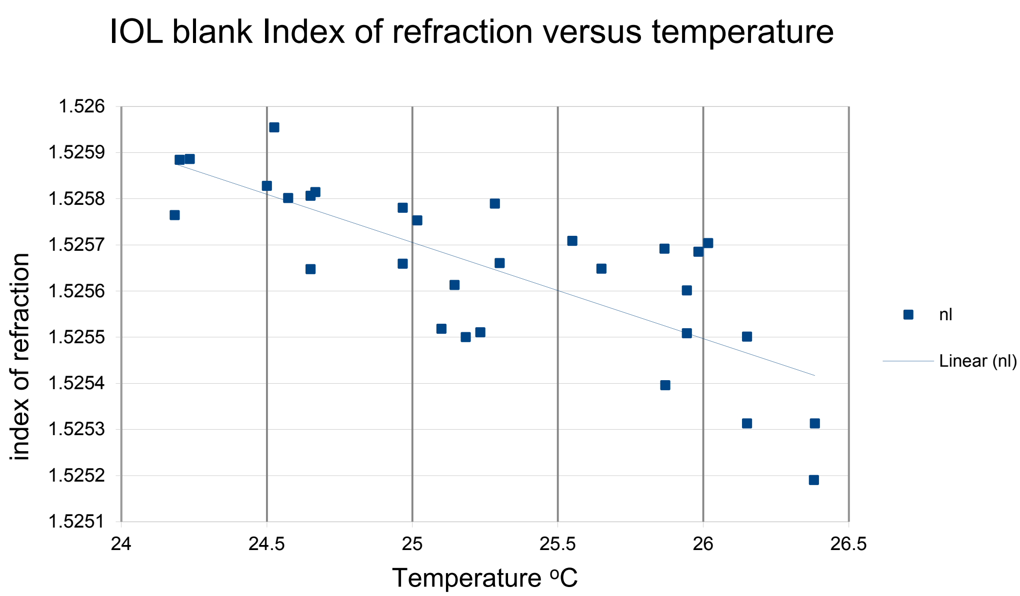

Figure 4. Index of refraction vs. temperature for IOL blanks for tests.

5. CONCLUSION

The developed measurement procedure, using the low-coherence interferometer in Lumetrics OptiGauge^{TM}, is capable of precise measurement of the refractive index of soft plastic materials in air, as well as in liquid environments. Measurement repeatability studies for the group refractive index at 1310 nm of plastic materials of contact lenses and intraocular lenses have been performed using multiple operators and instruments over the course of 80 days. The overall error in obtained refractive index of soft contact lenses with thicknesses below 250 μm was less than 0.001 when measured in saline solution. The error in the refractive index for 5 mm thick IOL lens blanks was less than 0.0002.

Table 6. Index of refraction measurement repeatability of IOL blanks.

Test #	date	Lens 1	Lens 2	Lens 3	Lens 4	Lens 5
1-A	07/11/13	1.52576	1.52582	1.52567	1.52552	1.52546
1-B	07/11/13	1.52577	1.52575	1.52557	1.52554	1.52550
1-C	07/11/13	1.52576	1.52585	1.52574	1.52550	1.52558
2-A	07/11/13	1.52563	1.52577	1.52588	1.52548	1.52554
2-B	07/11/13	1.52564	1.52579	1.52570	1.52552	1.52547
2-C	07/11/13	1.52568	1.52578	1.52586	1.52550	1.52568
3-A	07/15/13	1.52552	1.52537		1.52522	1.52532
3-B	07/15/13	1.52564	1.52555	1.52572	1.52521	1.52518
3-C	07/15/13	1.52579	1.52527	1.52528	1.52514	1.52544
4-A	07/16/13	1.52581	1.52586	1.52581	1.52559	1.52577
4-B	07/16/13	1.52574	1.52594	1.52609	1.52562	1.52570
4-C	07/16/13	1.52571	1.52586	1.52576	1.52563	1.52593
5-A	07/17/13	1.52549	1.52583	1.52552	1.52540	1.52547
5-B	07/17/13	1.52596	1.52566	1.52553	1.52566	1.52571
5-C	07/17/13	1.52563	1.52563	1.52575	1.52547	1.52587
6-A	07/18/13	1.52573	1.52591	1.52582	1.52569	1.52582
6-B	07/18/13	1.52567	1.52588	1.52584	1.52561	1.52585
6-C	07/18/13	1.52573	1.52608	1.52583	1.52568	1.52570
Lens Index of Refraction Statistics						
mean		1.52570	1.52575	1.52573	1.52550	1.52561
stdev		0.000110	0.000199	0.000181	0.000163	0.000203
max		1.52596	1.52608	1.52609	1.52569	1.52593
min		1.52549	1.52527	1.52528	1.52514	1.52518
range		0.00048	0.00081	0.00081	0.00055	0.00074
Temperature Statistics						
mean		25.15	25.32	25.43	25.45	25.50
stdev		0.65	0.54	0.50	0.52	0.56
max		25.87	26.12	26.15	26.23	26.38
min		24.18	24.65	24.97	24.95	24.87
range		1.68	1.47	1.18	1.29	1.51

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