Refractive index measurement through image analysis with an optofluidic device

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Abstract: We present a novel optical method, to our knowledge, to measure the refractive index of liquids by means of the images produced by an optofluidic lens. In addition we propose a new method to make optofluidic lenses.

OCIS codes: (120.0120) Instrumentation, measurement, and metrology; (100.2960) Image analysis; (120.4640) Optical instruments; (160.5470) Polymers; (160.4670) Optical materials; (010.1080) Active or adaptive optics.

References and links

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1. Introduction

Small adaptive optical elements are attractive due to their wide applications in compact optical systems. They can be used in cell phone cameras, optical communications systems, optical interconnects, CCD cameras, biomedical imaging systems and more [1]. Among the small optical components are the optofluidic lenses. One class of them usually has a cavity made of a glass substrate and a distensible PDMS (polydimethylsiloxane) membrane [2,3]. The membrane changes its curvature when the pressure of the liquid inside the cavity is increased or decreased. This membrane profile modulation will result in a tunable focal

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distance. In another class of optofluidic devices, the focal length can be tuned when different liquids are fed into a spherical cavity [4]. This cavity is in the bulk of a polymeric mixture. The lens focal distance changes when a liquid fills the cavity, thus modifying the local refractive index.

Typically refractive index measurements have been done with refractometers and inteferometers [5]. Refractometers like the Abbe, Pulfrich, Hilger – Chance and Pfund are based on the critical angle of total internal reflection. Interferometers like the Jamin and Rayleigh use interference of white light. Besides from these instruments, there is a new class of optofluidic devices capable of measuring the refractive index of liquid solutions [6–10].

Here we propose a novel optofluidic method to measure the refractive index of liquids based on an image-forming optofluidic lens. Formed images are susceptible of changes when different liquids are introduced in the lens cavity. By analyzing the images we can found their visibility which is in turn associated with the refractive index of the fluid inside the cavity. In section 2 we describe the optofluidic lens fabrication method. Section 3 mentions the liquids used in the experiment. Section 4 exposes the optofluidic lens characterization by image formation. Section 5 shows the lens calibration method to measure refractive index. Finally in section 6 we comment our results.

2. Lens fabrication method

Optofluidic lenses were made in the bulk of a transparent material. The inorganic material that we chose was silicone (polydimethylsiloxane, PDMS). This polymeric mixture is composed of repeating units of silicon and oxygen with carbon atoms as side groups. Silicone gels contain reactive silicone polymers and crosslinkers in a two component system. These mixtures cure with heat. We used an inorganic synthetic elastomer from Dow corning (Silastic T2) that is translucent with high strength and presents very low shrinking (0.1%). Its refractive index, measured with an Abbe refractometer, is 1.4152. The polymer is not affected by rain, snow, humidity, ozone and UV light for many years [11]. Thus it is expected that microlenses be stable during long time.

In Ref [4]. we have mentioned the fabrication of optofluidic ball lenses. These ball lenses give aberrated images due to their inherent large spherical aberration. To improve the images we now show a novel fabrication method. The optofluidic lens fabrication process is depicted in Fig. 1. First a plexiglass square is glued onto a glass plate. Then some silicone mixture is poured inside the square, Fig. 1a. A glass lens is placed in the silicone and then more silicone is poured. This set is left for overnight. After the silicone is cured the acrylic square is taken out, Fig. 1b. With a sharp knife the cured silicone is cut and the glass lens is removed, Fig. 1c. To seal the cavity a very small amount of uncured silicone is placed between the two halves, Fig. 1d. After curation time a “hollow lens” is found, Fig. 1e. A photograph of a finished lens is shown in Fig. 2.

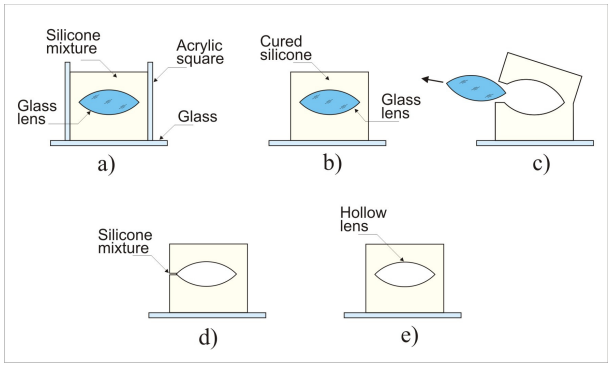

Fig. 1. Liquid lens fabrication sequence. a) Silicone mixture is poured in the acrylic square. A glass lens is inserted in the mixture. b) After curing acrylic square is taken out. c) silicone

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square is cut and the glass lens is taken away. d) Uncured silicone mixture is used to seal the cavity. e) Hollow lens is ready.

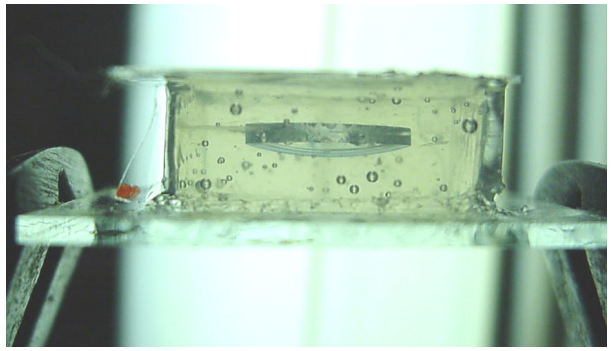

Fig. 2. Photograph of a hollow lens. Water with a dye was introduced (injected) to make visible the cavity.

In order to find out how well the process replicates the surface concavity and small features of the glass lens, we made the following test. A hollow lens was cut in two parts. One surface, and the corresponding one of the glass lens, was investigated with a surface analyzer. In order to plot the profiles of the glass lens and the silicone surface the raw data of the profilometer was first filtered using a Gaussian filter to eliminate the noise, which was mostly due to quantization. The profile of the glass lens can be seen in Fig. 3a). Figure 3b) shows the negative values of the silicone profile. In order to compare the profiles, the maximum of each profile was identified and one of the profiles was shifted so that the position of both maxima coincided. Then, the point by point difference of the more than 3000 points was calculated. The difference of one profile with respect to the other is shown in Fig. 3c. As can be seen, the difference in most part of the profiles is less than one micron. Thus we can say that silicone copies well the profile of the glass lens.

Glass lenses with different sizes and focal lengths were used in the fabrication method. For example lenses with the following characteristics were used: 8.5 mm dia. (plano-convex f = 10 mm), 8.9 mm dia. (biconvex, f = 6 mm), 5 mm dia. (biconvex, $f_{\#}5$) and 5 mm dia. (biconvex $f_{\#}10$).

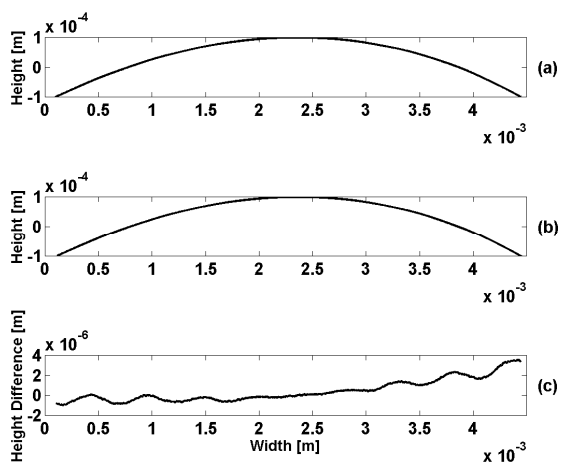

Fig. 3. Profiles of a) glass lens, b) lens cavity and c) the difference of both curves.

The path that light follows when passing through the hollow lens is shown in Fig. 4. Distance d_1 and d_2 are arbitrary and can be controlled during the fabrication method.

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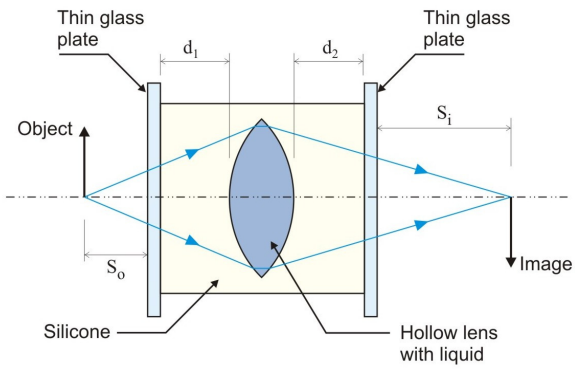

Fig. 4. Image forming by the hollow lens. S_o, object distance, S_i, image distance. Figure not to scale.

3. Optical liquids

The liquids used to fill the cavity should posses specific values of different properties. Namely, refractive index, thermal stability, low or null toxicity, compatibility with silicone, transparency and low cost, just to mention but a few. Liquids used in the experiments and their refractive index are listed in Table 1. An Abbe refractometer was used to measure the refractive index (at $\lambda = 589$ nm).

Table 1. Liquids used in the experiment

Liquid	Refractive index
Distilled water	1.333
Isopropyl alcohol	1.375
Ionic liquid	1.390
Ciclohexanol	1.450
Glycerol	1.472
Immersion oil	1.514
Bromonaphtalene	1.655

It is noticed that in Table 1 an ionic liquid (EMIM CF3 COO) is mentioned. Reference [12] deals with the application of ionic liquids in optofluidic devices.

For some experiments we needed liquids with a given refractive index. They were prepared with different ratios of water and sugar [13]. Refractive index obtained had the following values: 1.335, 1.340, 1.345, 1.350, 1.355, 1.360. Refractive index was measured with an Abbe refractometer. It should be noted that liquids were injected in the cavity with a syringe. At this time a second syringe was introduced in the hollow lens for air draining. The openings, due to the syringe introduction in the silicone, close when the syringes were taken away. This is due to the high elasticity of the material. Before attempting to do any measurements liquids should rest in the cavity for some time to let micro-bubbles disappear and fine particles to settle.

4. Lens characterization by image formation

Parameters that describe a lens are the radii of curvature (r_1 and r_2), index of refraction of the lens (n_l), the medium where the lens is embedded (n_m), its focal distance f and thickness, d. They are related by the equation: $1/f = (n_l - n_m)\,[(1/r_1) - (1/r_2) + (n_l - n_m)d/n_l\, r_1\, r_2]$. We notice that when the refractive index of the liquid in the cavity has the same value as the one the embedded medium shows, the focal distance is very large.

In our case we characterize one of the fabricated lenses that had the following characteristics: 4.8 mm dia., r1 = r2 = 4.7 mm, embedded in silicone. Distance from each vertex to the glass plate was $d_1 = d_2 = 5$ mm. Lens thickness 1.2 mm, Fig. 4.

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In order to find the behavior of the focal distance, as a function of the liquid refractive index in the hollow cavity, an object was placed at about 2.5 m from the lens. Its image was found with a microscope. The distance from the glass plate (Fig. 4) to the image plane was measured and was considered to be the Back Focal Distance (B.F.D.). Results can be seen in Fig. 5. Also in this figure have been plotted the theoretical points calculated with an optical design program. Liquids used in the experiment were mentioned before. We can see that experimental and theoretical points show a similar behavior but have a slight disagreement. We can mention some reasons of the disagreement. Theoretical points were calculated at the paraxial plane and not at the best focal plane. Instead Back Focal Distance was measured when a clear image of the object was obtained. This image lies in the best focal plane which is different from the paraxial plane. Other reason for the disagreement is the inherent lens depth of focus. During the experiment there was a range, not a given plane, where the image appears clear.

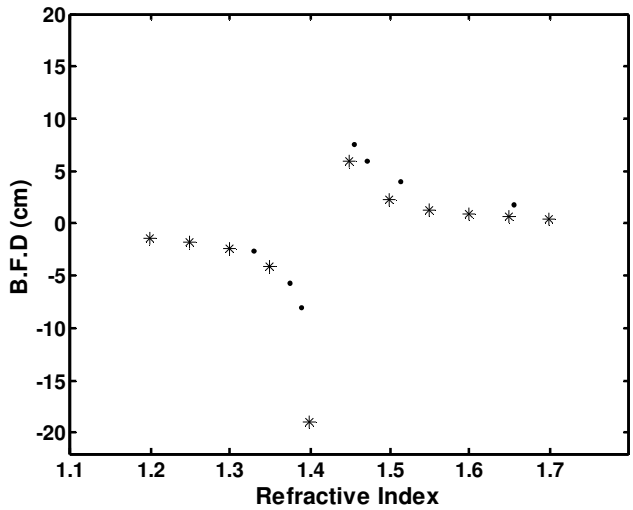

Fig. 5. Behavior of Back Focal Distance as a function of liquid refractive index. ● - experimental values, * - theoretical values.

Another characterization study was done considering the conjugate points. The same lens mentioned in the above paragraph was used. An USAF test chart was used as object. This was placed at given distances (S_o) and then the images (S_i) were found, Fig. 4. This experiment was repeated for the following liquids placed, one at a time, in the hollow lens: immersion oil (1.5145), bromonaphtalene (1.655), water (1.333) and isopropyl alcohol (1.375). The experiment was also simulated with an optical design program and these theoretical points are shown, together with the experimental ones, in Fig. 6. A resemblance in behavior of theoretical and experimental points can be seen.

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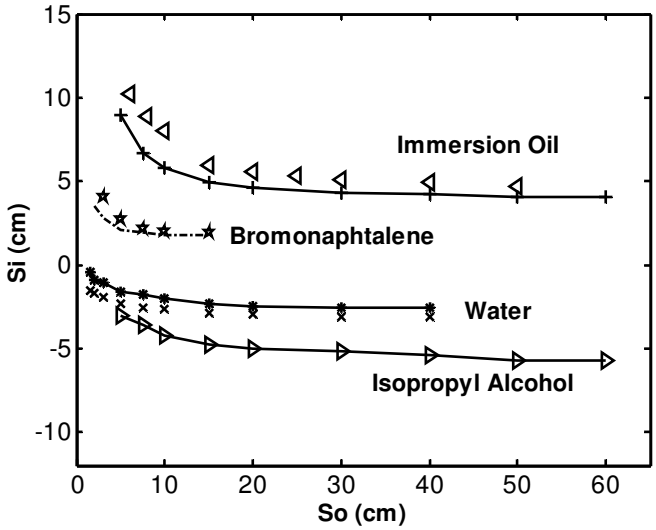

Fig. 6. Behavior of image distance, S_i, as a function of object distance, S_o. Experimental (continuous curve) and theoretical points are plotted. Parameter is the liquid in the cavity.

5. Image analysis and refractive index measurement

Recently a method to measure pressure based on image analysis was proposed [14]. In that case a flexible lens in a chamber was used. When the pressure increases, the profile of the lens changes. Thus, the image given by the lens, in a given plane, changes. By analyzing the visibility of these images a relation between pressure in the cell and the visibility can be determined.

Here we propose the following method to measure the refractive index by analyzing the images given by an optofluidic lens. The experimental configuration is shown in Fig. 4. In our case the object was a black stripe (4 mm wide) on a white background. This object was placed at 1.9 m from the lens. The optofluidic lens was the one described in section 4. Liquids fed into the lens, one at a time, had the following refractive index: 1.333, 1.335, 1.340, 1.345, 1.350, 1.355 and 1.360. These refractive indices have a lower value than the one silicone presents. Thus, the liquid lens will be negative giving virtual images. These images were seen with a low power microscope.

First a liquid was fed into the lens and the stripe image was found in a plane. As liquids were changed in the hollow lens the image, at the same plane, blurred. Some of the obtained images can be seen in Fig. 7. It is possible to notice that the first image shows a stripe with sharp edges. As liquids were changed the edges become blurred.

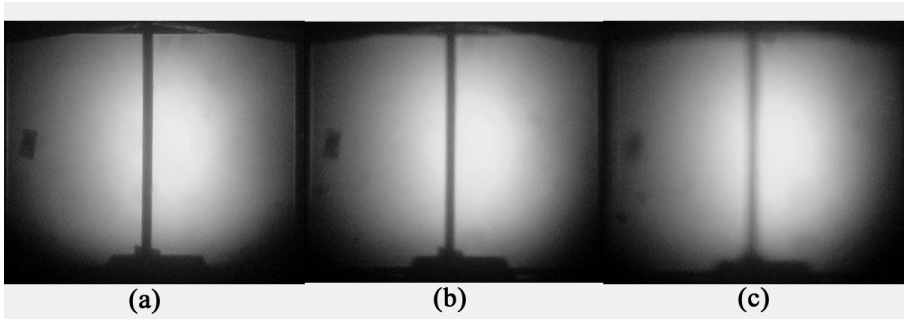

Fig. 7. Images given by a liquid lens when different liquids were fed into the cavity.

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Images were analyzed using computer software. To facilitate the analysis, 51x51-pixel sub-images were formed with the central area of the original images. The vertical black stripe was centered in each sub-image. To achieve the analysis, first, the gray level values of the pixels of the five central rows of each sub-image were averaged all along the rows. Thus, noise in the vertical direction was attenuated. The resulting one-pixel wide profiles were then filtered with a Gaussian filter to eliminate the remaining noise in the horizontal direction, Fig. 8. In Fig. 9 are plotted three of those profiles.

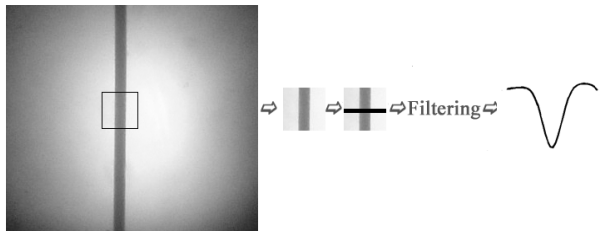

Fig. 8. Diagram showing the steps to get the gray level curve.

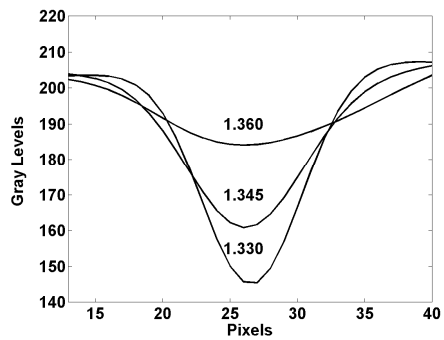

Fig. 9. Gray level as a function of pixel number. Parameter is the liquid refractive index.

We notice that when liquids with different refractive index fill the lens cavity the minimum gray level value of the corresponding curve rises. Remembering that the visibility [15] is given by V = (Imax – I min)/ (Imax + I min), in our case we take Gray Level_{max} and Gray Level_{min}, and applying this formula to the taken photographs we can get the behavior of visibility as function of liquids refractive index, Fig. 10. Software was used to determine the function that gave the best fit to the set of experimental measurements. Such function is represented by the continuous line in Fig. 10. The equation obtained is:

$$V = V0 + \left(\frac{A}{w\sqrt{\frac{\pi}{2}}} \right) \exp\left(-2\left(\frac{r - rc}{w} \right)^2 \right)$$

where $V0$ = 0.17488, rc = 1.36067, w = 0.02499, A = –0.00389, r = refractive index.

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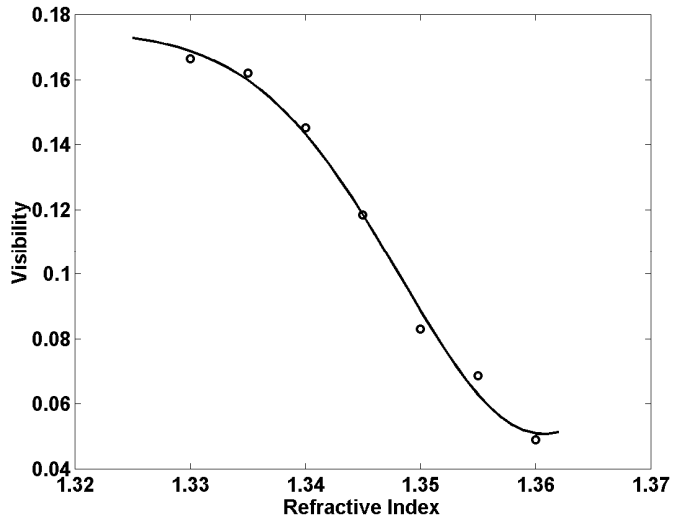

Fig. 10. Visibility of images as a function of the liquid refractive index. (o) - experimental values.

6. Conclusions and comments

Optofluidic lenses can be tuned by controlling the refractive index of the lens liquid or by controlling the shape of the lens. In the first case a cavity inside a polymeric mixture is made. In this work we have shown a method to fabricate these hollow lenses. Besides we have presented a lens characterization based on image formation. Finally we have described a method to measure the refractive index of liquids by analyzing the visibility of images given by an optofluidc lens.

The proposed method can be implemented in applications were it is necessary to measure the refractive index of liquids in real time. It is possible to connect the hollow cavity to the piping where a liquid flows. Then, the image of the black stripe given by the liquid lens can be captured by a camera and sent to a computer. There the refractive index can be calculated. If this index is outside a range a warning notice can be sent.

In addition, the optofluidic device is simpler when it is compared with, for example, the Abbe refractometer, since in this refractometer it is necessary to "load" the liquid between the prisms to be able to find the black-illuminated border by moving a knob.

Regarding the hollow lens precision, it can be calculated in the following way. By looking at Fig. 9 one can see that the difference between the minimum values of the two lower curves is about 17 gray levels. The difference in refractive indices is 1.345 – 1.330 = 0.015. Thus, by dividing 0.015/17, 0.00088 is obtained. This is about one thousandth of refractive index per gray level. This precision is not as good as that of the Abbe refractometer which is accurate up to the fourth decimal point. However, we could improve the hollow lens precision if we use cameras which give images with more than 8 bits of depth (more than 256 gray levels). Besides we could use more than 7 liquids to find the calibration curve of Fig. 10.

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