Optofluidic variable focus lenses

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Here we propose optofluidic spherical microlenses that can change their focal distance by varying the refractive index of the liquid that composes them. These lenses are fabricated in the bulk of a polymeric mixture. Results of a characterization study of the profile of the lenses, the image forming capability, and the behavior of the focal distance as a function of the refractive index are presented. Ionic liquids are suggested as a source of liquids useful for fabricating this type of lens. © 2009 Optical Society of America

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1. Introduction

Optical materials consist mainly of solids such as glasses, crystals, and plastics. However, liquids are also often used in, for example, microscopes, refractometers, and dye lasers. Microscopes use liquids such as immersion oil to increase brightness and resolution when large numerical objectives are used. Refractometers use liquids to measure the refractive index of plastics, glasses, crystals, and more. Also liquids are used to allow the inspection of bulk flaws in glasses and gemstones.

The miniaturization process is present in fields such as electronics, fluids, and optics. Today microelectronic circuits can be found in devices such as radios, cellular telephones, computers, and many more. Microfluidics [1], or the manipulation of fluids moving in small channels, is a fairly new field that is applied in biotechnology, chemistry, materials science, and physics. Micro-optics [2] comprises the design, fabrication, and testing of optical elements with sizes of about some hundreds of micrometers (or less) to about 1 mm. Among the microelements are lenses, mirrors, gratings, polarizers, and more. These microelements can be refractive, reflective, or diffractive.

Combining the fields of micro-optics and microfluidics, the optofluidics [3] field was created. It comprises the manipulation of light and fluids at the microscale. Optofluidic devices can be used in biochemical sensing, for example. Among the optofluidic elements are microlenses. The shape of their surfaces can be modified by changing the implied liquid pressure [4–6] or electric field [7,8] and become convex or concave (i.e., their positive or negative focal distance can be changed at will).

Here we propose microfluidic lenses that can change their focal distances not by changing the curvature of its surfaces but by changing the fluid refractive index that composes them. We distinguish between two classes of lenses: passive and dynamic. The first class is a liquid lens, with a given refractive

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index, that is immersed in a medium. The second class is a hollow lens, also immersed in a medium, which can be filled with a liquid having the desired refractive index. In Section 2 we describe a theoretical work about the performance of a traditional optical system and that of a microfluidic one. In Section 3 we talk about the application of ionic liquids as a means for changing the refractive index of microlenses. In Section 4 the lens fabrication method of passive and dynamic liquid lenses is described. In Section 5 we present a characterization of microlenses comprising their profile, image forming capability, behavior of focal distance as a function of refractive index, and behavior of conjugate distances.

2. Theoretical Behavior

In this section we describe, with the help of an optical design software, the behavior of two optical systems. We consider a simple liquid spherical lens immersed in air and a spherical lens in a cell filled with a polymeric mixture. The cell has a certain length. With this study we try to produce a reference with which to judge the microfluidic lens that we propose. We have assumed that the diaphragm is in the first surface of the lens.

In Table 1 are the characteristics and results of the studied systems. Lens refractive index, radii of curvature, and thickness are the same for the two systems. Regarding the results that comprise the back focal distance, *f*-number, longitudinal spherical aberration, and wave aberration, we see that the values of the lens in the cell are larger. The aperture for the lens in air is larger. The *f*-number shown in the table is the one that lets the marginal ray enter without total internal reflection in the second surface of the lens. In summary we can say that the lens immersed in air is faster, i.e., it collects more light, and its longitudinal spherical aberration is smaller.

3. Ionic Liquids

Among the characteristics that an optical liquid should present are specific refractive index and dispersion, thermal stability, low toxicity, system compatibility, transparency, and low cost. Ionic liquids show thermal stability, low toxicity, good transparency, and low cost. They are compatible with silicone, the material where microfluidic lenses will be embedded.

Table 1. Characteristics of Spherical Lenses in Air and in a Cell Filled with Polymer

	Lens in Air	Lens in a Cell with Polymer
Refractive index of surrounding medium	1	1.4126
Lens refractive index	1.4584	1.4584
R1	1.1 mm	1.1 mm
R2	1.0 mm	1.0 mm
Thickness	2.38 mm	2.38 mm
Back focal distance	0.567 mm	7.9 mm
f-number	0.85	5.85
Longitudinal spherical aberration	−0.51 mm	8.6 mm
Wavefront aberration	55.79	60.14
Aperture	2.09	2.03
Best image position	0.308 mm	3.57 mm

Ionic liquids (ILs) are organic salts, typically composed of a large organic cation and an inorganic polyatomic anion, that are liquids at or close to room temperature. IL properties largely depend on the cation and anion nature. These molten salts have a number of interesting chemical and physical properties. Based on these, a broad range of applications in chemistry, physics, and industry have been reported [9]. Applications of these materials include optical and magnetic switching, optical communication, sensors, and the fabrication of liquid mirror telescopes [10]. Some of them possess liquid crystal properties and large negative nonlinear refractive indices and thermo-optical coefficients [11].

In our study we employed the following ionic liquids: (a) [EMIM] [BF_4], (b) [BMIM] [BF_4], (c) [EMIM] [Tf_2N], (d) [BMIM] [Tf_2N], (e) [EMIM] [CF_3COO], and (f) [BMIM] [CF_3COO]. In Table 2 is shown the refractive index of the mentioned liquids. Because we wanted to cover a range of values of refractive index, we choose [EMIM] [BF_4] (1.4352) as the starter liquid. Then we mixed it with different amounts of distilled water (1.333) to have lower refractive indices and with glycerol (1.4726) to have higher values of refractive index. With this method we covered the range between 1.333 and 1.4726. Two other liquids were used without mixing with [EMIM] [BF_4]; they were immersion oil (1.51) and bromonaphtlene (1.63). A description of the synthesis procedure [EMIM] [BF_4] is given in Appendix A.

4. Passive and Dynamic Liquid Lenses Fabrication Method

To behave as a lens, a liquid should be in a container with curved surfaces. For lenses having sizes of about centimeters or larger, a glass or plastic container could be made. However, for microlenses it is difficult to make a container with good spherical shape. Having in mind this difficulty, we propose the following fabrication method.

A. Passive Lenses

The liquid microlens is fabricated inside a cell that is composed of a square (11 mm × 11 mm × 8 mm) plastic rim that is used as a periphery structure. The bottom and top of the rim are sealed with thin (150 μm thickness) or thick (1 mm) pieces of flat glass. The cell

Table 2. Refractive Indices of Ionic Liquids

Compound	Refractive Index
[EMIM] [BF_4]	1.4352
[BMIM] [BF_4]	1.4195
[EMIM] [Tf_2N]	1.4225
[BMIM] [Tf_2N]	1.4265
[EMIM] [CF_3COO]	1.4056
[BMIM] [CF_3COO]	1.4278

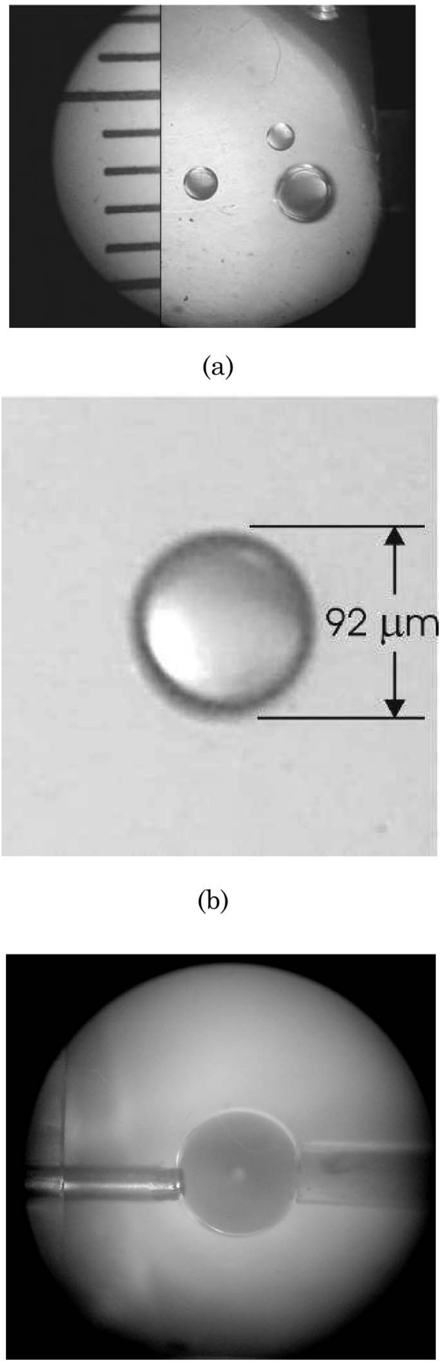
will contain two materials: the first one will fill the whole cell, and the second one will be embedded in the first material and will form the spherical liquid lens. We have chosen silicone as the first material. Then to form the lens, a syringe, having a thin needle, is inserted in the silicone, and some amount of ionic liquid is injected. Due to the pressure of the silicone all over the surface of the injected liquid, a sphere is formed. The dimension of the lens is a function of the amount of injected liquid. Usually for lenses with a diameter of some hundreds of micrometers, just a fraction of microliters is needed. After the liquid is injected, a time of about 24 h is left to pass to let the silicone cure and become an elastomer. At the end of the process a spherical lens is found within the polymer.

In Fig. 1(a) are shown three water liquid lenses made with the described method. A dye was incorporated in the water to increase the contrast between the polymer matrix and the lens. We found that microlenses with sizes from tens of micrometers to about some millimeters can be made. In Section 5 we mention some characteristics of the lenses.

In the preceding paragraph we mentioned that silicone was the polymer used to fill the cell. In general, silicones or polysiloxanes [12] are inorganic polymers containing repeating units with silicon and oxygen, and with carbon atoms as side groups. Different forms of the same material can be produced, namely, gels and thermosets. Silicone gels contain reactive silicone polymers and reactive silicone cross linkers in a two-component system. Mixed together, these materials have a soft, compliant feel when cured and stick to substrates without migrating. Viscosities can be adjusted with the molecular weight of the polymers.

In this work an inorganic synthetic elastomer, made from a cross linked silicone polymer, was used to obtain the microlenses. The polymer was reinforced with a filler. A commercial silicone formulation from Dow Corning (SILASTIC T2, a translucent high strength silicon rubber) was employed. This formulation is a two component system that cures very fast with heat. It is mixed in a proportion of 10∶1 with the curing agent and shows a very low shrinkage upon curing (0.1%). According to the producer, it is expected that the polymer be virtually unaffected by rain, snow, humidity, ozone, or the Sun's damaging (UV) rays for many years [13]. Based on this, it is expected that the obtained microlenses be stable during a long time. At the end of the process, silicone presented a refractive index of 1.4126, measured with an Abbe refractometer.

One parameter that should be considered in the microfluidic lens fabrication is the diameter of the needle used to inject the liquid. To make small passive lenses (tens of micrometers diameter) we used capillaries with an outside diameter of about 100 μm. In Fig. 1(b) is shown a water lens of about 90 μm diameter. For lenses with diameters of several hundred micrometers, needles have a size of about 200–300 μm. For larger lenses, needles of 800 μm were used. When dynamic lenses are made, it is necessary to consider that the needle will remain attached to the spherical hollow lens after the liquid has been injected. If a too large needle is used, the final lens will not show a spherical shape but an ellipsoid one. Besides this, care should be taken when



(a)

(b)

(c)

Fig. 1. (a) Three passive lenses are shown. Scale is in millimeters. Lenses are not in a plane. Due to this, some of them are out of focus. (b) Water lens. (c) Dynamic hollow lens filled with water. Diameter is 1503 μm.

choosing the needle if liquids with high viscosities (high refractive indices) are used.

B. Dynamic Microlenses

To fabricate dynamic lenses, two holes are made in the rim of the plastic cell. They are drilled in opposite sides. In one of them a needle is introduced, and in the other a capillary. Then the liquid is injected. With this method, at the end of the process, one extreme of the spherical lens is in contact with the tip of the syringe and the other with the capillary that is used to drain the liquid or trapped air. In Fig. 1(c), one of such dynamic lens can be seen.

5. Characterization of Liquid Lenses

A. Profiles

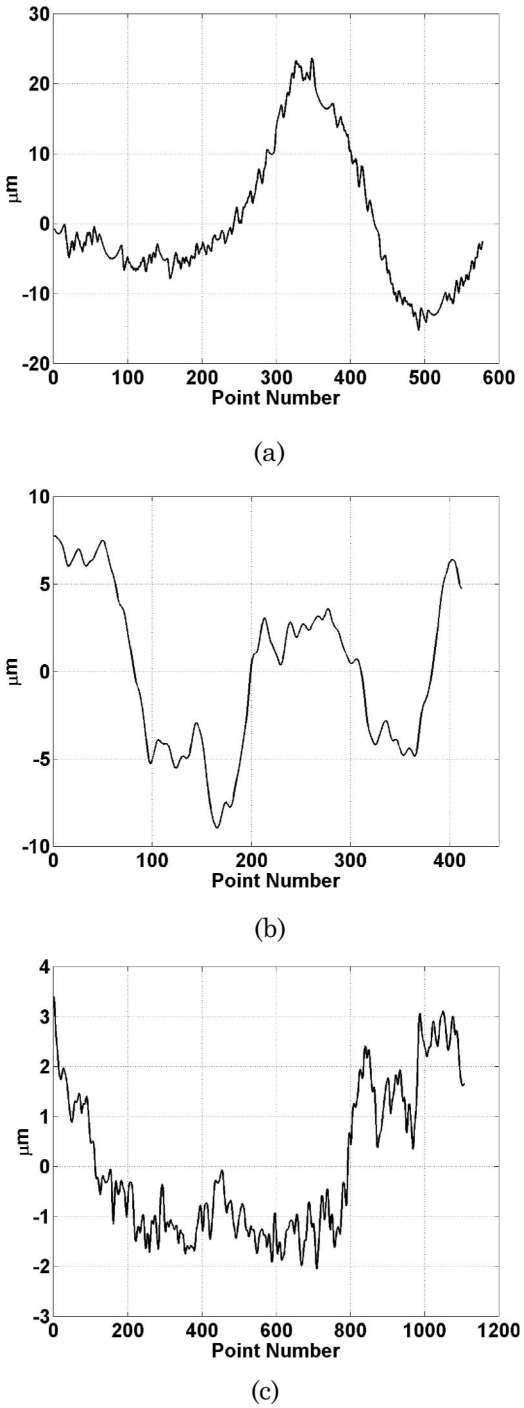
The form and optical characteristics of passive and dynamic liquid microlenses were investigated. For the first point, photographs of the lenses were taken through a microscope. Then with an image processing method, a comparison between the profile of the lens and a theoretical circle was done. The following describes this operation.

First, the outer border of the lens was segmented (i.e., it was separated in a single image). Then three points from the profile were taken to obtain the radius and the coordinates of the center of a theoretical circle. We compared this theoretical circle with the actual profile of the lens by subtracting the distance from the center to each point of the profile. In Fig. 2 the deviation of the profile from the best fitting circle, for a passive and a dynamic lens, is plotted. The axis of the abscissa corresponds to the pixel number that belonged to the rim. From Figs. 2(a) and 2(b) it is possible to see that the deviation of the passive lens surface from a perfect circle, in most of the selected profile, is no more than 20 μm. This value is small if we consider that the diameter of the lens is 566 μm. For the dynamic lens [Fig. 2(c)] deviation is also small, about 3 μm. Diameter of the lens is 600 μm.

B. Image Forming

Capability of microlenses to form images was tested in the following way. Two optical configurations were considered: an object far from the lens and an object close to the lens. In the first part the object was placed about 3 m from the lens. This distance was considered large in comparison with the diameter of the lens. In Fig. 3(a) is shown the real image given by a passive liquid lens (~700 μm diameter) of an object consisting of three vertical and three horizontal bars, each of 7 cm × 1.5 cm. Liquid used to form the lens had a refractive index of 1.4583. Regarding the dynamic lenses, in Fig. 3(b) is seen the virtual image given by a lens having a diameter of about 2 mm filled with water. The object was a laser warning logo with dimensions of 35 cm × 25 cm.

To test capability of lenses to form real amplified images when the object was close (~5 mm) to the window of the cell, a USAF test target was used as an object. A real image given by a passive positive lens (~1 mm diameter) is shown in Fig. 3(c). We can notice some blur, possibly due to the spherical aberration. The photograph shows that group 6, element 3 is resolved, or 80 line pairs/mm (12.5 μm between bars).



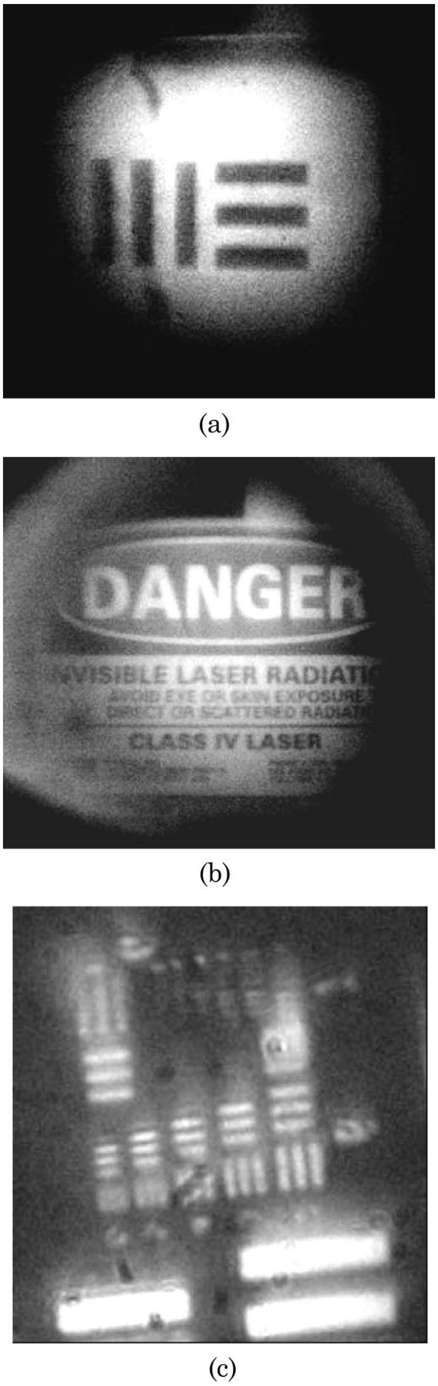
(a)

(b)

(c)

Fig. 2. Deviation of spherical lenses profile with reference to the best-fitting circle. (a) and (b) show a passive lens (diameter 566 μm). (a) Side view, (b) upper view, (c) dynamic lens upper view. Dynamic lens diameter 600 μm.

Repeatability of the fabrication method was tested by making several lenses with the same amount of water (0.7 μl). This was done with the help of a microsyringe. All lenses were in the same plane. Results can be seen in Fig. 4(a). The diameters of the lenses, beginning with the upper left in a clockwise direction, were 1098 μm, 1098 μm, 1133 μm, and 1160 μm. An optical design program was used to calculate the focal distances of the embedded lenses. Focal lengths were −6.55 mm, −6.55 mm, −6.74 mm, and −6.94 mm, respectively. The third and fourth lenses show a difference in focal length of 3% and 6%, with respect to that of the first two.



(a)

(b)

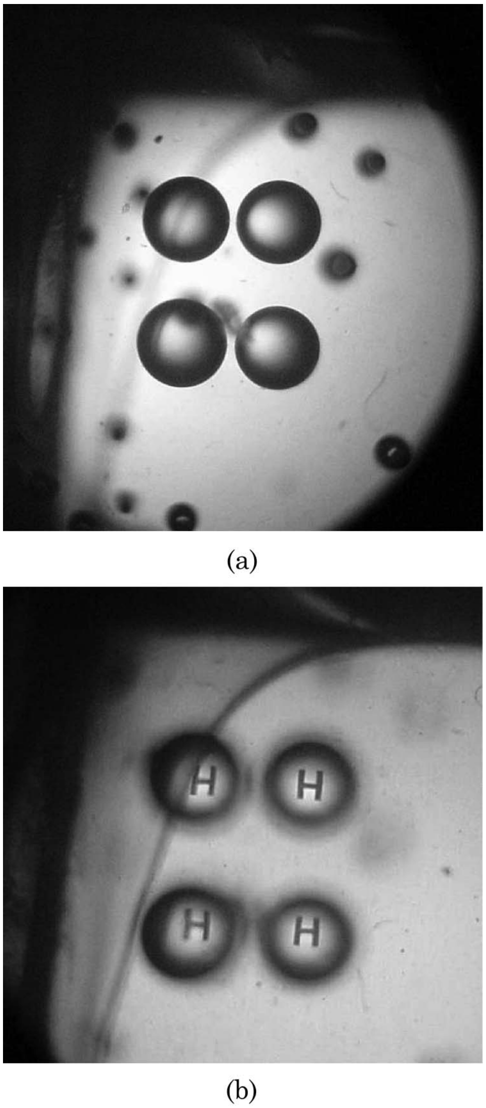
(c)

Fig. 3. (a) Real image given by a passive lens (700 μm diameter) of an object placed 3 m from the lens. Bar size was 7 cm × 1.5 cm. (b) Virtual image given by a dynamic lens (2 mm diameter) of a logo warning with a size of 35 cm × 25 cm. (c) Image given by a passive lens (1 mm in diameter) of a USAF test chart placed at 5 mm from the lens.

Lenses in Fig. 4(a) were tested to form a virtual image of a letter “H”. Results can be seen in Fig. 4(b). It is noticed that three lenses formed a good image, while a lens of a larger diameter formed a slightly blurred image. This is due to its larger (6%) focal distance. That is, the image produced by this lens was not in the plane where the other images laid. This shows that differences of up to 3% in focal length do not produce noticeable effects in the image formation process.

C. Dynamic Lens Focal Distance as a Function of the Refractive Index

To find the relationship between the focal distance and the refractive index, an object was placed about

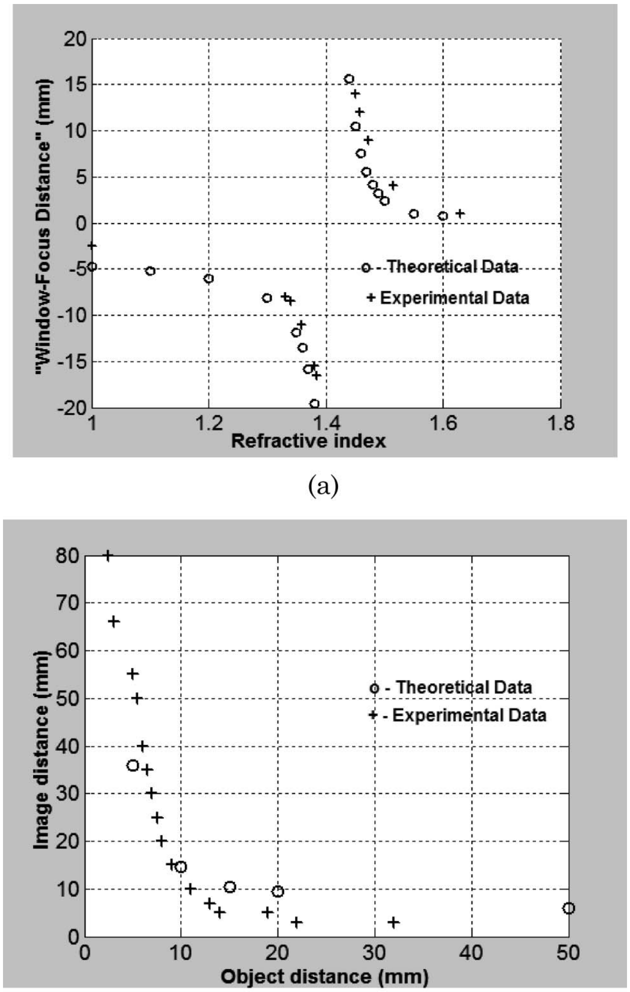


(a)

(b)

Fig. 4. (a) Array of water lenses. Each was made with the same amount of liquid (0.7 μl). Diameter of the upper lenses is 1.098 mm. All lenses were in the same plane. (b) Images that each lens gave of letter “H” placed beneath the array. Notice that image given by the lower left lens is slightly blurred. See text for explanation.

4 m from the lens, and the plane of the image, virtual or real, was found with a microscope. The distance from the plane to the back window of the cell was measured each time the refractive index was changed. This distance was called window–focus distance, or WFD. For a given lens, results can be seen in Fig. 5(a). Besides the experimental points, we have plotted the points given by an optical design program that simulated the experiment. The following parameters were considered: radius surface $1 = 1.1$ mm, radius surface $2 = 1.0$ mm, refractive index of the polymeric medium 1.4126, thickness of the lens $t = 2.38$ mm, windows thicknesses and refractive index 1 mm and 1.5. The lens was not centered in the cell, but it was 2.2 mm from the first window and 3.5 mm from the last window. It was assumed that the diaphragm was in the first surface of the lens. The lens showed an ellipsoidal shape. This is the reason why a different radius of curvature was taken in each face. As can be seen in Fig. 5(a), theoretical and experimental points show a similar behavior. In the simulation process we have supposed that the best images lie where the paraxial ray meets the optical axis. However, due to the high spherical aberration, the best experimental image could not be located in the plane of the paraxial image but, probably, some millimeters away. Besides this, the depth of focus phenomena also affects the measurements.



(a)

(b)

Fig. 5. (a) Behavior of the window–focus distance as a function of refractive index for a dynamic lens. (b) Behavior of the image distance as a function of the object distance for a passive lens.

D. Conjugate Points of Passive Lens

To find out the conjugate points of a passive lens, an experiment considering the object–lens and lens–image distances was performed. A USAF test chart was used as object. Results are shown in Fig. 5(b). This experiment also was simulated with an optical design program. The following parameters were considered for a spherical lens: radius of 1.4 mm, refractive index of 1.4583, refractive index of the polymer 1.4126. The lens was not in the center of the cell; it was 5.4 mm from the first window and 1.2 mm from the second window. We can see a resemblance of the behavior of the theoretical and experimental points. Again, we cannot expect a good agreement between curves due to the spherical aberration and the depth of focus phenomena mentioned before.

6. Comments and Conclusions

It has been shown that it is possible to fabricate spherical hollow microlenses in the bulk of a polymeric mixture. The fabrication method is simple and inexpensive. The focal distance of the lens can be changed by inserting different liquids in the lens. The profile of the lenses, in two perpendicular planes, has been studied, and it suggests that the lens shape is close to a sphere. The image forming capability of microlenses, when an object is close to or far from the lens, has been shown. For dynamic lenses, the behavior of focal distance as a function of the liquid inside the lens has been shown.

An application where dynamic lenses could be used is in the measurement of a liquid's refractive index. In [14] a prototype to measure the refractive index is described. Such a prototype comprises basically an input optical fiber, a capillary (that contains the liquid), and an output fiber. The input fiber illuminates transversally the capillary, which behaves as a cylindrical lens. After light emerges from the capillary, the beam shows a narrow ellipsoidal cross section. At the center of this beam the output fiber is placed to collect light. If the liquid in the capillary is changed by another with a different refractive index, the intensity of the collected light will change. The dynamic spherical lens that we made in this work could replace the capillary. By doing this, the cross section of the light emerging the spherical lens will show a circular shape. Thus the alignment of the fiber would be much easier.

Regarding the optical bandwidth of the devices, we can say the following. Each device consists of two glass plates, silicone, and liquids. These components show high transmission in the visible region. Besides this, we have made the experimental tests with white light sources. Thus the optical bandwidth of the devices is the visible region.

Due to the nature of the formed spherical lens, it presents high spherical aberration that degrades the quality of the images and affects the measurements of the focal distances. However, its simple fabrication method, low cost, and possibility to change the fabrication parameters, including the refractive index of the liquid, makes the microfluidic lens a versatile optical element.

Appendix A

In this section we mention the ionic liquids' synthetic procedure:

Chemicals used in the fabrication were the following: 1-ethyl-3-methylimidazolium chloride, 1-ethyl-3-methylimidazolium bromide, 1-buthyl-3-methylimidazolium chloride, 1-buthyl-3-methylimidazolium bromide, 1-buthylpyridinium bromide, silver (I) oxide, silver trifluoroacetate, and bistrifluoromethanesulfonimide lithium salt; they were purchased from Fluka and used as received. Tetrafluoroboric acid (48 wt. % solution in water), activated charcoal, deuterium oxide, 99.9 at. %D, acetone-d_6 99.9 at. %D (1% v/v tetramethylsilane) were purchased from Sigma-Aldrich and used as received.

Synthesis of $[\mathbf{EMIM}]^+$ $[\mathbf{BF_4}]$. Tetrafluoroboric acid (22.34 mL, 0.171 mol, 48% solution in water) was slowly added to a stirred slurry of silver (I) oxide (19.83 g, 0.0855 mol) in 50 mL distilled water over a period of 10 min. After silver (I) oxide was completely consumed, a solution of 1-ethyl-3-methylimidazolium chloride (25.0 g, 0.171 mol) in 150 mL distilled water was added to the reaction mixture and stirred at room temperature for 2 h. The white precipitate of silver (I) chloride was filtered off, and the solvent was removed at 65 °C under vacuum. The resulting salt is a pale yellow liquid [15].

Purification of Ionic Liquids. A certain amount of charcoal was added into the ionic liquid solution and kept overnight. Charcoal was then removed by filtration, and water was evaporated under vacuum. The resulting ionic liquids are usually colorless or light brown. Some ionic liquids were purified by passing them through a column with silica gel and activated charcoal [16].

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