Optofluidic compound microlenses made by emulsion techniques

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Abstract: Here we present a new method to make liquid lenses. It is based on the microfluidics method and involves the preparation of emulsions one drop at a time. Tests of lenses by image formation are presented. Experimental results are compared with results of an optical design program. We also present a new type of lens that we call a Compound Lens which consists of two spherical lenses, one inside the other.

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1. Introduction

The fields of optics and fluidics have given birth to the discipline of optofluidics [1]. Devices that belong to this recent discipline are liquid core waveguide structures [2], microfluidic dye lasers [3] and interferometers [4], variable focus liquid lenses [5], variable apertures [6] and photonic crystal fluidic fiber dye lasers [7] to mention but a few. One of the key optofluidic components are microlenses. They can be classified as passive or active elements depending on their function. Active variable focus lenses can achieve their function by varying their refractive index [8] and/or by changing the curvature of their surfaces [9]. Modification to the curvature can be made by pressure [9] or by electro-wetting [10]. Here we present a novel method to fabricate liquid microlenses. This method is based on the procedure to prepare microfluidic emulsions [11]. The paper is organized as follows: in section 2 some basic characteristics of emulsions are briefly reviewed; section 3 presents the microlens fabrication method; section 4 describes a characterization of the lenses made by image formation and lateral magnification behavior; in section 5 we present the fabrication method of a novel compound liquid lens. This lens is made with two liquids, each one forming a sphere, but one inside the other. A theoretical study of the compound lens, by an optical design program, is discussed. Finally in Section 6 some comments and conclusions are included.

2. Emulsions

The basic structure of colloids [12] consists of a dispersion phase inside another (continuum) phase. The dispersed phase has particles with sizes ranging from molecular size up to several microns. Colloid systems have a variety of properties depending on the nature of the components and are thermodynamically stable and metastable. These metastable colloids are obtained by nucleation and grow by fragmentation.

Emulsions are metastable colloids. They are made of two (or more) immiscible fluids. Small droplets of one liquid are dispersed in another liquid. The dispersion is usually not stable and the droplets can come together, by coalescence or ostwald rippening, and form two layers. Emulsions can be stabilized from coalescence by adding surfactant molecules. These molecules migrate to the liquid-liquid interface and inhibit droplet coalescence. Surfactants are wetting agents that lower the surface tension of a liquid, allowing easier spreading, and lower the interfacial tension between two liquids. Surfactants are amphiphilic, i.e., they contain hydrophobic and hydrophilic groups and can assemble in the bulk solution into aggregates. Such aggregates are vesicles and micelles. The concentration of surfactant at which surfactants begin to form micelles is known as the Critical Micelle Concentration or CMC. Surfactant molecules can be considered as having a "tail" and a "head". When oil micelles form in water, the tails of surfactant molecules (lipophilic) dissolve in oil and form a core that encapsulates an oil droplet. The ionic polar heads (hydrophilic) form an outer shell that maintains contact with water. Surfactants can be anionic, cationic, non-ionic, and zwitterionic or dual charge. Vesicles can be visualized as a bubble of liquid within another

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liquid. The bubble is separated from the outside liquid by a bilayer. If there is only one bilayer they are called unilamellar vesicles; otherwise they are called multilamellar.

Thus, emulsification consists of dispersing one fluid into another by the creation of an interface. Properties of emulsions are governed by temperature, composition and the droplet size distribution. Emulsification can be achieved with methods such as high pressure homogenization and membrane-, microchannel- and spontaneous- emulsiffication.

Emulsions frequently consist of drops that are highly polydisperse in size. To overcome this difficulty methods such as microchannel emulsification have been developed to gain better control of size drops.

The microfluidic process is a microchannel emulsification method. It is an alternate and versatile method to make emulsions. An emulsion fabricated with a microfluidic device makes one drop at a time. The result is a monodispersed emulsion. With microfluidic devices it is also possible to make double, triple or even higher order emulsions. This means that inside a drop, for a double emulsion, there is another drop of different material.

Emulsions are involved in food [13–15] and cosmetic industries [16]. They are also drug carriers in medicines, food and pesticides. In optics they have been used for self-focusing beams [17] and for laser speckle reduction [18].

3. Microlens fabrication method

The fabrication of micro-lenses was carried out using the microfluidic method described below. Some chemicals, including a surfactant, are dispersed in a phase that constitutes the continuum medium. Then with a syringe the dispersed phase is injected in the continuum medium. Due to the surfactant action and the pressure in the continuum medium, which is the same in all directions, a sphere is formed. Though the lens is spherical it can behave like a convergent or divergent lens. For convergent lenses the dispersed phase refractive index is higher than the one of the surrounding (continuum) medium. The opposite is true for negative lenses. We made positive lenses with liquids such as dodecanol (refractive index= 1.445), immersion oil (1.51), mineral oil (1.469), and silicone oil (1.44). The surrounding or continuum medium was water (1.333) mixed with ethyl alcohol (1.3664). To make negative lenses we used water for the lens and immersion oil for the surrounding medium.

Positive lenses made with immersion oil were made with the following method. First a mixture of deionized water (10 ml) + 40 mg SDS (Sodium Dodecyl Sulfate) + 62 mg NaCl was prepared to form the continuum medium. This mixture was placed in a glass cell. Then immersion oil was injected with a syringe having a fine tip with an inner diameter of about 0.3 mm. The amount of injected oil was less than a microliter. When the drop of oil was injected it had the tendency to move upwards. This is so because the density of oil is lower than that of the water. In order to match the density of the water with that of the oil we added several drops of ethyl alcohol to the water until the oil drop remained still in the water. The photograph in Fig. 1a shows the glass cell, the needle, an immersion oil drop and scale (smallest division = 1 mm). Fig. 1b shows a mineral oil lens in water.

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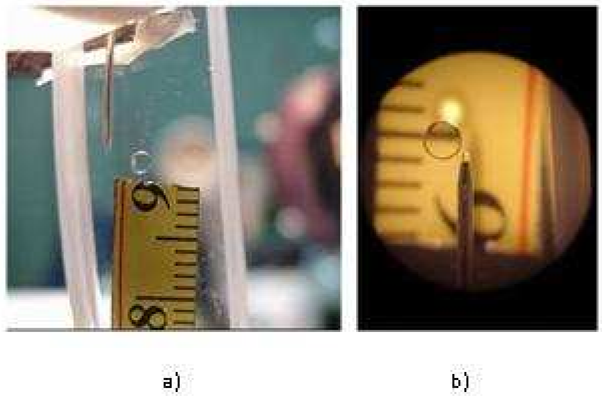

Fig. 1. a) Example of an immersion oil lens. Scale is in millimeters. Notice the needle of the syringe and the glass cell. b) A mineral oil lens in water. Notice a small drop emerging from the needle.

To investigate the microlens profile an image of a lens (Fig. 2a) was processed to enhance its contrast. The border of the microlens was located using the Sobel algorithm [19]; then, with the help of a commercial drawing program the center of the lens was located and a one-pixel wide circumference was sketched as shown in Fig. 2b. As can be seen, the shape of the lens is practically spherical. The maximum deviation from the sphere is less than one pixel which is quite probably due to quantization; that is, the difference between the actual analog value and the quantized digital value. This error is due either to rounding or truncation.

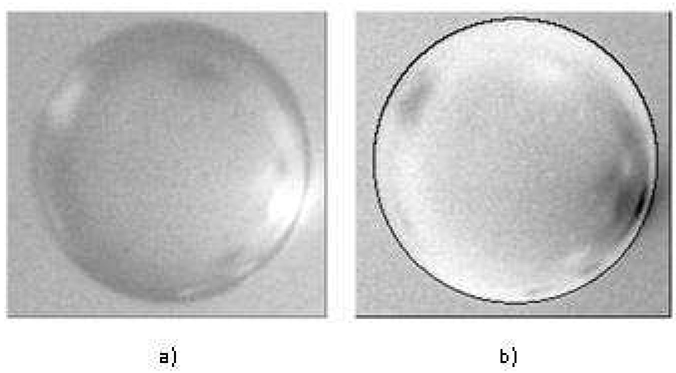

Fig. 2. a) Image of a microlens. b) An image processing procedure was used to segment the outer border of the lens shown in black pixels.

The size of the fabricated lenses is in the range of 100 µm to several millimeters. However, we suppose that if a special syringe, that could deliver nanoliters [20], was used lenses with smaller diameters could be made.

4. Image formation, lateral magnification, and lens Gauss law.

4.1 Image formation

As an example of image formation with liquid microlenses made with the emulsion techniques, we present the results obtained when an immersion oil lens was considered. The lens had a diameter of about 2 mm. Two cases were considered: object near the lens and object far from the lens. The object used in the experiments was a USAF test target. In the first case the target was positioned 5 cm from the lens. The image given by the lens was investigated with a microscope and is shown in Fig. 3a. It was noticed that element 6 of group

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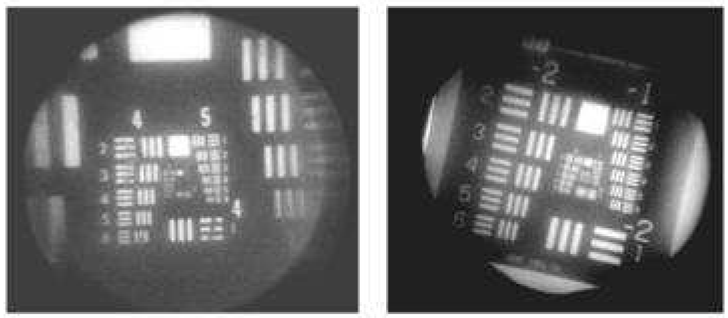
5 of the target was resolved (57 lp/mm). In the second case, the test target was positioned at 56 cm from the lens. The image seen with a microscope is shown in Fig. 3b. Group 1, element 1 was resolved (2 lp/mm). Calculating the angle subtended by a pair of lines of element 6, group 5, and the angle subtended by a pair of lines of element 1, group 1, at the mentioned distances from the lens, we see that this angle is almost equal (0.004 degrees) for the two positions. Thus the resolving power of the lens is similar when the object is far from or close to the lens.



a) b)

Fig. 3. Images given by an immersion oil lens. a) When object (a USAF test target) was 5 cm from the lens. b) When object was 56 cm from the lens.

4.2 Lateral magnification and Gauss's Law

To investigate the magnification behavior of the liquid micro-lenses an experiment was performed. Lateral magnification, as a function of the distance between the lens and the object, was determined. A USAF test target was used as object. Object distance (Xo,) measured from the glass cell wall, was varied in steps of different length. In every step a photograph of the image given by the lens was taken. By measuring the images and knowing the object size, magnification was determined. Results can be seen in Fig. 4a for a positive lens, oil in water, and for a negative lens, water in oil, in Fig. 4b. We can see a resemblance of the behavior of the theoretical and experimental points. In these plots theoretical results, calculated with an optical design program, are also shown. For the oil lens the following parameters have been considered in the calculations: oil refractive index 1.51, water refractive index 1.333, lens diameter 1.2 mm, front distance from vertex of the lens to the wall of the cell 5 mm, back distance 1.2 mm, thickness of the cell wall 1 mm. The theoretical model for this oil lens give us an effective focal distance equal to 1.923 mm which is measured from the second principal plane located at -2.017 mm from the last surface of the cell. For the water lens data considered were: diameter of the lens 428 µm, front distance from the cell 3.5 mm, back distance 4 mm. The effective focal distance for this water lens is -0.535 mm, which is measured from the second principal plane located at -3.457 mm from the last surface of the glass cell.

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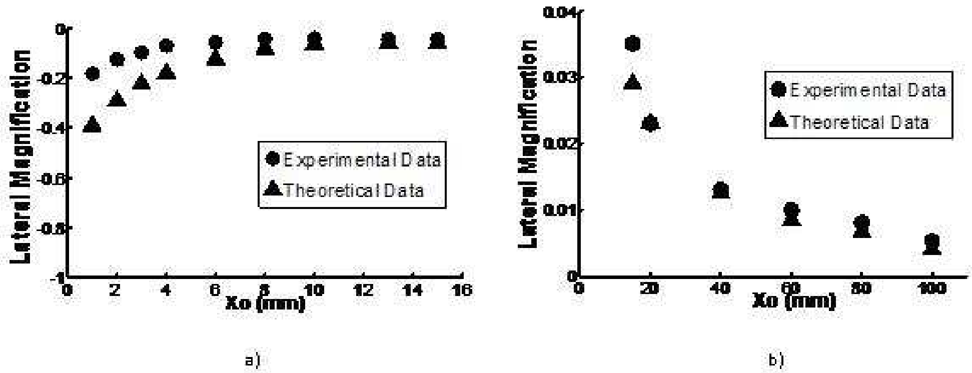

Fig. 4. Behavior of Lateral Magnification as a function of the distance between the lens and object. a) For an immersion oil lens in water (positive lens), b) for a water lens in oil (negative lens).

Considering the lens parameters and information in Fig. 4a and 4b, we obtained the behavior (Gauss´s law) of the image distance (Xi) versus object distance (Xo) of both lenses. Xo and Xi are measured from the first and last surface of the glass cell, respectively. These behaviors are shown in fig. 5a, for the oil lens (positive), and in Fig. 5b, for the water lens (negative).

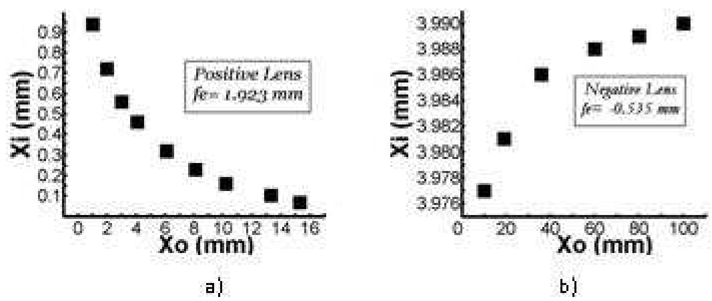

Fig. 5. Behavior of the Image distance (Xi) versus Object distance (Xo) for a) an oil lens in water and b) water lens in oil.

5. Compound lenses

In certain applications it is desirable to have optical systems that could give images in two different planes. Diffractive lenses show this behavior [21]. They can form virtual images and real images at the same time. Another method to achieve this double image is by making the profile of a lens with two different curvatures [22]. For example if the center of the lens shows a positive curvature this part of the lens behaves like a positive lens and it will give a real image. But if the periphery of the lens has a different curvature, say a negative one, this part of the lens will give a virtual image.

Another method to make a lens that gives real and virtual images, at the same time, is the one that has one refractive index in the center and another refractive index in the periphery. This situation is difficult to achieve with glass lenses but can be done with liquid microlenses. We have called this type of system a compound (double) lens.

The procedure to make a liquid double lens, one inside the other, is the one that is used to make a double emulsion [12]. First a mixture of water + NaCl + SDS is prepared and poured in the cell, this is the continuum phase. Then a given quantity of immersion oil, the dispersed phase, is injected into this mixture and a positive lens is made. Then, some of the first water

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mixture is injected inside the immersion oil lens. Thus, a negative lens is made inside the positive lens. In Fig. 6a a diagram of the double lens is shown and in Fig. 6b the real system is shown.

To test the double image formation by the double lens an object consisting of circular and radial lines was placed at 5 cm from the lens. With a microscope the images, real and virtual, were observed. In Fig. 6c the virtual image given by the negative inner lens can be seen. Fig. 6d shows the image given by the positive immersion lens.

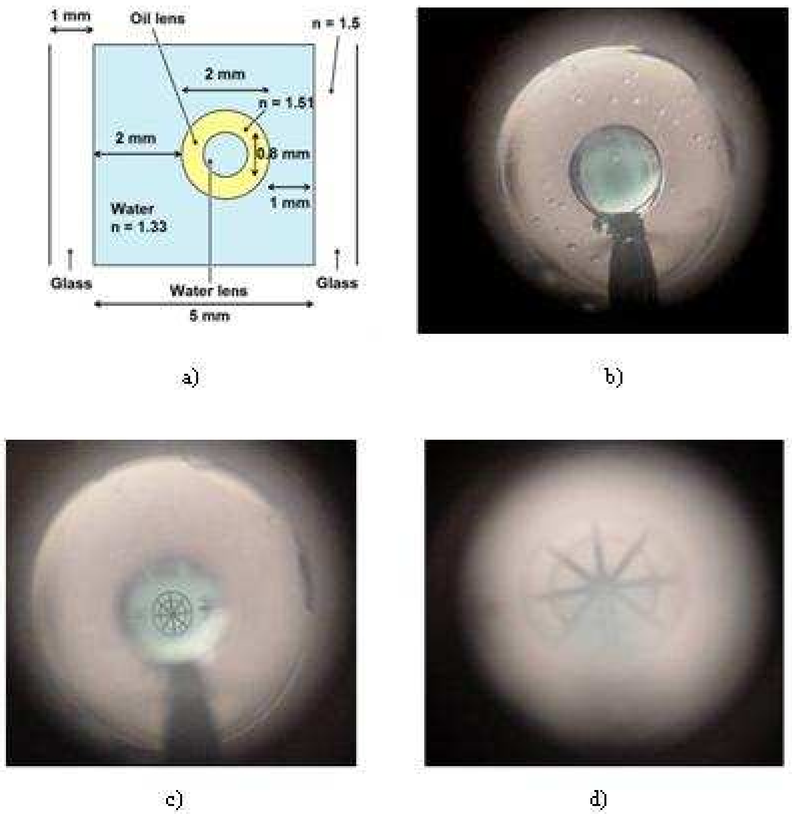

Fig. 6. A double lens. a) Diagram showing the characteristics of a double lens. b) Photograph of a fabricated double lens. c) Virtual image given by the central lens. d) Real image given by the outside lens.

To understand the image formation procedure by the double lens its behavior was modeled with the help of an optical design program. Data given to the program is shown in the scheme of Fig. 6a. It was assumed that an object point was located on the optical axis at 120mm from the first plane surface of the glass cell. The result of the design program is shown in the ray trace diagram of Fig. 7. Four rays coming from that object point have been plotted to show the image formation. The rays passing through the two concentric lenses emerge as a diverging beam that forms a virtual image located behind the two lenses whereas the rays that only pass through the outer spherical lens will emerge as a convergent beam that forms a real image located outside the container. As can be seen in Figure 8, the transversal spherical aberration, TRA, for the rays forming the real image is larger than the transversal spherical aberration of the rays forming the virtual image. This result is expected since the rays forming the real image cover a larger aperture than the other rays. This explains why the image in Fig. 6c is clearer than the one shown in Fig. 6d.

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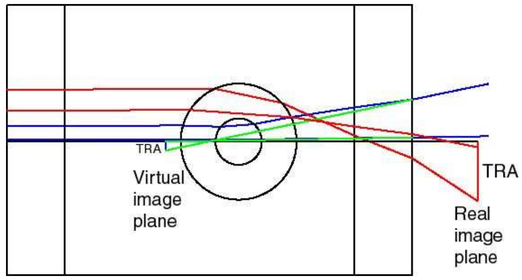

Fig. 7. Ray trace diagram of a double lens. Characteristics of the lens are displayed in Fig. 7a. Notice that a virtual image and a real image are present at the same time. Transversal Spherical Aberration TRA is larger for positive lens than for negative lens.

6. Conclusions and comments

We have shown that it is possible to make spherical lenses inside a liquid environment. The method used to make the lenses was the same as that used to prepare microemulsions. It is possible to make positive and negative lenses with sizes between a hundred microns and several millimeters.

By studying the lenses it was found that their profile was spherical. Also, by studying the images formed by those lenses their lateral magnification behavior was found. Later by means of an optical design program the behavior of the image distance versus object distance was obtained.

We have shown that it is possible to make double lenses, i.e., one lens inside the other. This type of lenses can give virtual and real images at the same time. With this in mind it would seem to be possible to make lenses with several layers.

Because this research is the first made on liquid microlenses more studies should be done to find better fabrication methods and their optical characteristics. We have managed to keep the liquid lens floating in the continuum medium by matching the densities of the continuum medium and the medium of the lens. This step is more critical when a compound lens is made. The material that forms the inner lens should have the same density as the material that forms the outer lens. If this is not the case the inner lens will rise to the surface or sink. Thus, the two lenses will remain off-center affecting the quality of the image. In Fig. 6b we have shown a compound lens. The tip of the syringe keeps the inner lens in position. However, it is possible to make the compound lens without having the tip of the syringe. In Fig. 8 we can see one of such lens. It can be seen that the inner lens is slightly off- center and a small bubble can also be seen.

Fig. 8. A compound lens.

Microfluidics science has evolved, and there are new devices that can be used to make better emulsions. We consider that if those devices could be used to make liquid microlenses these will be better made and will perform better. For example, they will have better mechanical and chemical stability and sets of lenses with the same characteristics, such as focal length and diameter, could be made. Also, by selecting and studying the fluids that form

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the continuum and lens media better lens configurations could be made. Probably, arrays of microlenses in a desired place within the glass cell could be constructed.

The size of the lens could be controlled with microfluidics devices, thus controlling the refractive index and the lens size, a desired focal length could be obtained.

Regarding the materials used to make the lenses, and the medium that contains them, we have used only a few. However, there are more materials that could be used. This is convenient because if a given refractive index is desired it is quite possible that a given liquid will show it. Besides, a new class of liquids is being developed that could be used in the liquid lens fabrication. These are the Ionic Liquids [23], previously called molten salts. These salts show melting points below 100 ^{o}C and they are made of heterocyclic nitrogen-containing organic cations and inorganic anions. These ionic liquids are an alternative to harmful chemicals [24].

At present we can foresee the application of liquid microlenses in thermal sensing using Whispering-Gallery-Mode (WGM) optical resonators [25]. Nowadays microlenses used with this technique are made of inorganic materials such as silica and silicon. Also organic materials, such as polydimethylsiloxane (PDMS), have been used [25]. Basically, the optical configuration used to make thermal measurements consists of a tapered optical fiber and a microsphere. Light from a tunable external cavity laser is coupled through the fiber taper to the microsphere. This fiber taper also helps to couple light out of the microsphere. The tapered section of the optical fiber evanescently excites the WGMs in the microsphere. The fiber output light is detected by a photodetector connected to a oscilloscope to measure the transmission spectra. The thermal effect of the WGM in the structure of the microsphere results from the temperature-induced changes in the refractive index and the diameter. Thus there is a resonant wavelength shift. We suggest that instead of using silica or PDMS microspheres, liquid lenses could be used.

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