Tunable liquid lens based on electrowetting technology : principle, properties and applications

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Abstract: *A new principle of variable lenses with tunable focal length will be demonstrated : two iso-density non-miscible liquids are trapped inside a transparent cell. The liquid-liquid interface forms a drop shape. The natural interfacial tension between liquids produces a smooth optical interface, which curvature is actuated by electrowetting. In addition, in order to have a usable lens, it is necessary to incorporate a centering mechanism, such that optical axis remains stable. Intrinsic physical limitations will be presented as well as actual performances of the technology. Several applications will be discussed in the autofocus/macro/zoom optics for CMOS and CCD miniature imagers*

1. Introduction

In the past 2-3 decades, the need for miniaturization of optical systems has increased dramatically, especially in coherent light handling, for various applications including communications, data storage, security or personal identification. More recently this trend has extended to imaging systems. Nowadays camera modules, integrating a digital sensor and an optical system altogether, have entered into mobile phones and slim digital cameras, bringing the need for developing miniature optical systems.

The camera module were developed first with low count pixels and ultrasmall format sensors (CIF resolution, single element lens), but the need for better image quality leads now to the development of megapixels sensors, 1/4" or less. These sensors are now commercially available, but the need for autofocus and zoom compound lenses remains open: no commercial solution exists up to now at reasonable prices for this very large scale market. The liquid lens technology that we present here could be the solution to this demanding applications.

2. Principle of the liquid lens

The Fig 1 shows how to use electrowetting for realizing an optical lens which can be used in mobile applications. Fig. 1 (a) shows the usual electrowetting phenomenon [1] which enables to change the shape of a water drop on a insulator film by simple voltage application.

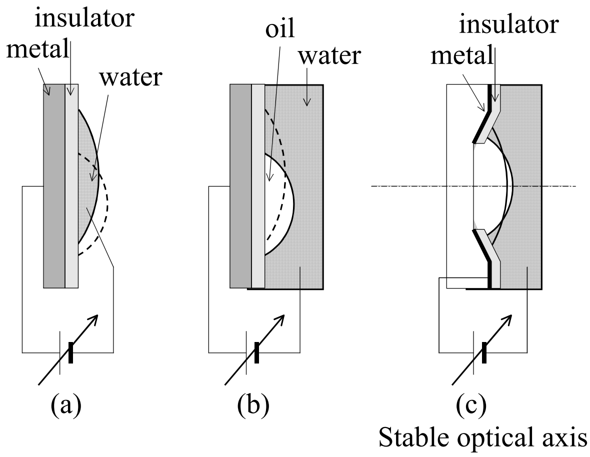


Figure 1 : from electrowetting to working liquid lens

In order to make a usable lens, the key features which are important to bring are [2]:

- Two non miscible liquids of the same density: instead of having a water drop in air, one works with water and oil. This condition is necessary for suppressing any optical distorsion of the gravity on the liquid-liquid interface, which enables to use the lens in every orientation, as shown in Fig. 1 (b).
- Inversion of the conducting and non conducting fluid. In current electrowetting experiments, the water is used as a drop immersed in the non conducting fluid (air). For application, it will be preferable to work with a drop of the insulating fluid (oil) immersed in the conducting fluid (water). This is to avoid any optical perturbation of the liquid-liquid interface due to the liquid meniscus at the electrode touching the conducting fluid. It is preferable to use an oil drop immersed into a conducting fluid (water based solution) which

can be connected to the outside without perturbing the liquid—liquid interface, as in Fig. 1 (b). This inversion is not strictly necessary, as in former publications it is mentioned that contact could be made through the insulating layer [3]. Nevertheless, in practical realization, the inversion of oil and water is preferable.

- Centering mean [4,5]: some publications have mentioned in the past how to use small liquid droplets as optical lenses [6], but if this lens has to be inserted in a more complex system, it needs precise alignments of optical lenses. The fig 1 shows that if no centering mean is applied, the drop can freely move in the transverse directions while the focal length is changed. We have the experience of such random displacements which prevent to use the lens.

The liquid-liquid interface thus needs then to be precisely controlled and any physical realization of lenses have to incorporate such a centering mean This centering of the liquid-liquid interface can be obtained by several ways. The following are given as example, and many others can be found :

- applying electric field gradient [4] using variable thickness of the insulator film.
- the natural gradient present at the edge of an electrode can be used [4,7]. In the case of lenses developed by Lucent, a decentering force can be applied through angular sector electrodes. Such decentering force can only be used if a centering force (restoring force) exists, such that the balance between the decentering forces and the centering forces can bring a stable equilibrium. Although this was not explicitly discussed in the publications of Lucent, we believe that in their case the centering effect comes either from the edge effect of the ring electrode, or from the gap between sector electrodes, which could play this role too, if well designed.
- it can also be obtained as a result of the geometry of the supporting surface for the two fluids [5]. It has been shown that inwards cones, cylinder and some toroïdal shapes are centering surfaces for the liquid-liquid interface [4,5]. Cylinder insides and cylinder edges have also been proposed [4,8,9]. On the contrary, some surfaces having an inward high curvature are not suited for centering the liquid-liquid interface. Detail analysis of the classification between centering and decentering surfaces will be given during the talk.

3. Properties of the liquid lenses

This paragraph is intended to show the basic results one can get from liquid lenses. The figure 2 below shows the response curve of the lens: 1/f as a function of the applied voltage, where f is the focal length (m) and V being the applied voltage. In this case this is an ac voltage and the value corresponds to rms. On the same curve, one shows the experimental points corresponding to increasing (squares) and decreasing voltages (circles), revealing very small hysteresis. The modeling of the lens response, according to the basic theory of electrowetting [1] is shown as a continuous line.

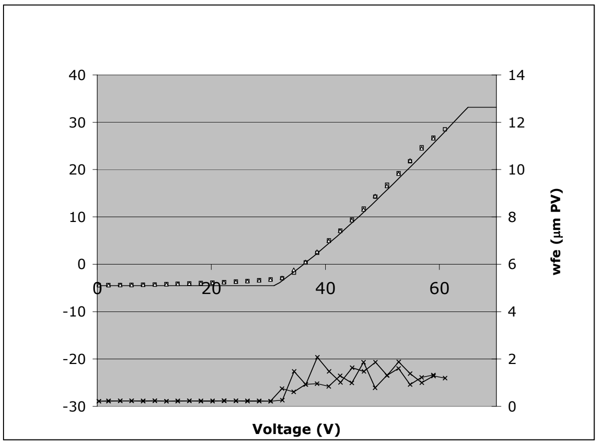
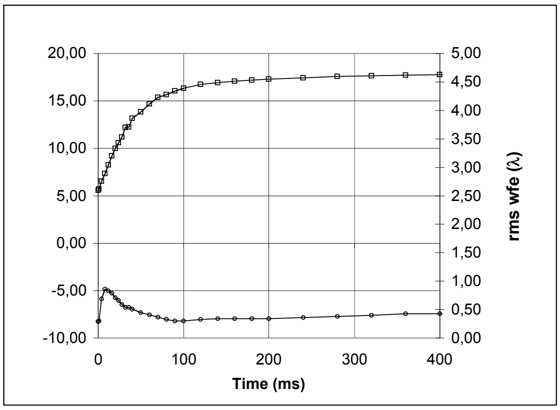


Fig. 2 : optical power (dioptries) as a function of applied voltage

On the lower part of the Figure 2 is shown the Peak to Valley (PV) of the residual wave front error (wfe) after the passage through the lens, corresponding to the error to the best approaching spherical wavefront, as a function of the voltage. These values are indicative, and should not be taken as intrinsic, as the wfe clearly depends on the quality of the lens manufacturing.



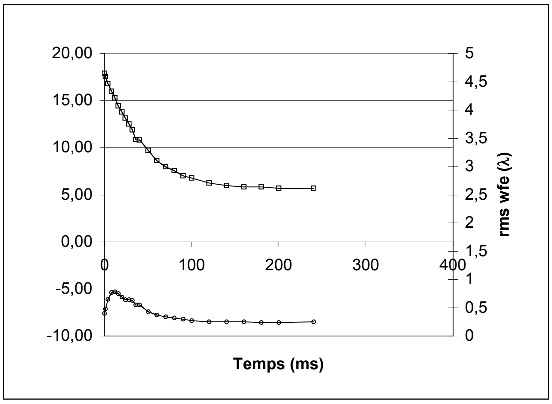


Fig. 3 : transcient behavior of the liquid lens after

An abrupt voltage step between 40V and 50V. (a) increasing voltage step. (b) decreasing voltage step.

On the figure 3 above, we show the dynamic response of the lens, after a voltage step, upwards or downwards between 40V and 50V. The response of the inverse focal length is shown as squares, revealing a response which is close to exponential with a typical response time of 50-200ms. The residual wave front error is shown also during the whole dynamic step as open circles. One can observe a slight transient degradation of the lens quality during the voltage step, the lens returning to full quality after 100 ms.

On the electrical point of view, the lens is equivalent to a capacitor (with a varying capacitance with voltage).

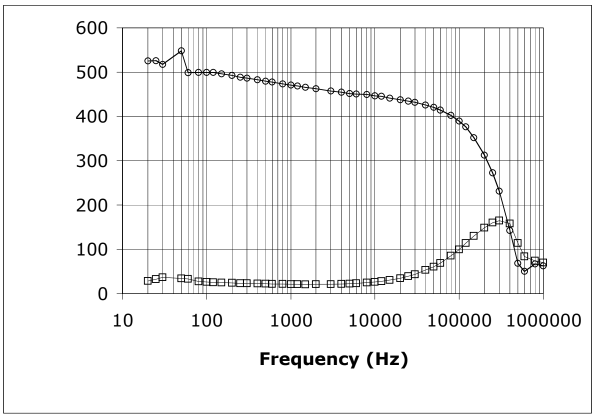


Fig. 4: dielectric response of the lens as a function of frequency.

The figure 4 shows the typical result of the capacitance and loss factor (shown as the real and imaginary part of the dielectric susceptibility) as a function of the applied frequency. This shows a rather flat behavior up to 200kHz where the dissipation is due to the finite conductivity of the electrolyte. From the curve of fig4, one can estimate that the dissipation inside the lens at 1kHz will be of the order of 0,7mW.

4. applications

Applications of the liquid lenses based on electrowetting can be found in many areas. Typical possible sizes for the lens pupil range from less than a millimeter to one centimeter, using the current technology. This makes this technology ideal for millimetrtic lenses needed now in the mobile phone applications. The very small power consumption (less than one mW dissipated in the lens) is also a great advantage compared to conventional motorized systems.

All electronic sets integrating optics could benefit from the simplicity of this technology. Optical pickups, displays, cameras, computers etc... Again the size under consideration is well fitted between macro- and microscopic systems. Of course photonic professional applications could also present good opportunities for our technolgy.

Many other applications could be envisaged. The liquid lens is one adaptive optical components, with a huge amplitude, but rather limited flexibility on the pattern of phase shifts, limited to what can be done with a liquid-liquid interface. Directly every application where Z scanning is required could be of interest: the dynamic behavior shown in tis paper demonstrates it is possible to apply to the lens a triangular ramp (eventually damped in order to avoid schocks generated at the reversing of the ramp) in order to use the full range of dioptric correction upon very fast scans. Telemetry could use focus information in order to produce 2D and 3D images at quite good resolutions.

Medical applications could also be very promising, as endoscopes develop on many complex optical functions including confocal microscopy or Optical Coherent Tomography [10].

As a final remark, lasers could be monitored or controlled by the liquid lens. Liquids can sometimes produce interesting properties as materials, which could be of use, even in high power pulsed laser systems.

9. References

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