LIQUID LENS TECHNOLOGY: PRINCIPLE OF ELECTROWETTING BASED LENSES AND APPLICATIONS TO IMAGING

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Abstract : The principle of liquid lenses based on electrowetting will be presented, with emphasis on the key features that enables to produce a useful component for complex optical systems: equality of the densities of the two non miscible liquids, centering mean for the liquid-liquid interface which allows the optical axis to remain always stable, choice of the suitable insulating material for the supporting body etc… We will present experimental results discussed in the light of a modelization.

1. INTRODUCTION

Recently a number of new optical applications have arisen, which require a high degree of miniaturization. Photonics, optical communications, optical sensors, optical pick-up for CD/DVD reading or writing, as well as miniature cameras for the security or the consumer electronic markets are demanding optical parts in the 1-10mm range. Whereas the realization of lens elements of this sizes is well mastered, using plastic or glass materials, the problems of actuation of such lenses for bringing autofocus, or zooming functions is still a challenging problem.

Optical engineers have naturally looked at adaptive optics coming from high-end scientific world to correct the wavefront curvature, in order to enable closed loop servo.

Variable focus lenses offer these optical functions while having no moving part. There have been a number of principles of variable focus lenses which have been experienced since about 60 years, starting with the work of Graham[1] who developed a principle of deformable chamber filled with liquids. More recently the work of many companies of industries has been oriented to produce solutions at a very small scale. Liquid crystals actuators have been known since a long time to produce wave front corrections, which are easy to configure in a fully addressable 2D pattern. Several practical realizations have come though, as in the group of Commander et al[2]. Recently a simplified version has been produced by Naumov et al[3], using a special design of electrodes which allows a gradient of electric field, thus producing a variable focal lens. The main drawback of the liquid crystal lens is that the amplitude is rather small, achieving a few dioptries of optical power variation.

In the recent past[4-6], we could introduce a new principle of liquid lenses based on electrowetting. While the principle of manipulating a liquid droplet was known since a long time[7-8], these principles were restricted to a single lens element systems, due to the lack of precise control of the optical axis.

One can show that major advantages of these liquid lenses are coming from the small electrical dissipation, the reduced size, the long lifetime under voltage cycling (which is a side advantage of the no-moving part principle).

In this paper, we will review first the operation of the liquid lens, on a given design example. The second paragraph will then examine quantitatively the most important feature of the liquid lens design: the centre-alignment of the liquid drop. Then we will present experimental results of our current lens, comparing with the theoretical model.

2. PRINCIPLE OF THE LIQUID LENS DESIGN

Figure 1 shows examples of a liquid lens structure: between two glass windows, two non miscible liquids are trapped in a closed cell. One of the liquid is based on a water solution and thus it is conducting electricity. The other liquid is apolar, and should be non conducting (the oil phase). The natural interface between the liquids thus forms a natural diopter, due to the index difference of the two liquids.

The actuation of the liquid-liquid interface is using electrowetting, which enables to change the relative wettability of the two liquids by a simple voltage application. In these conditions, the liquid-liquid interface has a spherical shape, with a variable radius of curvature.

In order to work properly, the liquid lens needs several key features:

- Density requirement: the two liquids should have exactly the same density. This allows the lens to work in every possible orientation: optical axis, horizontal, vertical or in any orientation to gravity.

This density equality is tuned by allowing a small adjustment of the liquid composition (mixture of dense and less-dense fluids).

- A centering mean for controlling the stability of the optical axis when the voltage is applied. The two configurations above are representing two different ways of achieving this stability (see the next paragraph).
- An integral liquid-liquid interface: it is important that the design allows to have conducting phases to be connected to the outside world without having to touch physically the liquid-liquid interface.

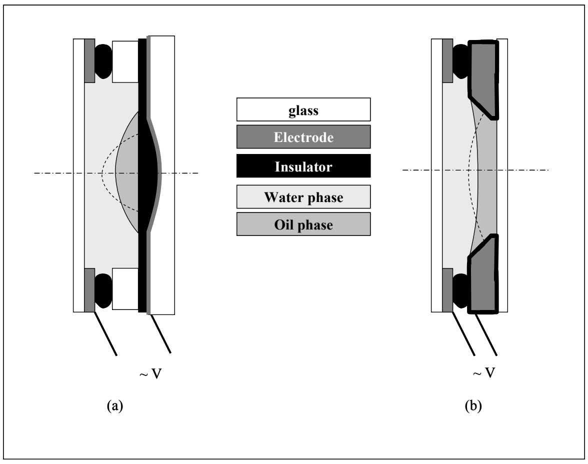


Figure 1: two examples of the liquid lens practical realization. Upon voltage application the liquid-liquid interface is dislaced. The continuous line shows the zero voltage situation. (a) gradient configuration. (b) geometrical centering.

In the following chapter, we will consider in details the centering of the liquid drop, discussing the relative advantages of the configurations shown above.

3. CENTRE ALIGNING THE LIQUID DROP

We will discuss the two different configurations of the liquid drop shown in the figure 1.

Centering by a dielectric thickness gradient

We will analyse the configuration of fig. 1(a) first: here the centering of the drop is obtained through a gradient of the electric field. The Figure 2(a) shows the principle of electrowetting: the contact angle of the oil drop on a planar surface which is made of an electrode covered with an insulator film of thickness "e" and of dielectric constant "ε" is well described with the following equation:

$$\cos(\theta)=\cos(\theta_0)- 1/2\ \varepsilon\varepsilon_0 / (e\gamma)\ V^2. \qquad (1)$$

It can be shown from eq (1) that for a 60V actuation, using a low-k dielectric (e.g. polyethylene ε=2,4) using liquids with a liquid-liquid interfacial tension of about 30mN/m, leads to a thickness of the dielectric film of about e=1,3µm. The electric field in the dielectric is then of the order of E= 0,4 MV/cm. This E-field is quite high, significantly below the dielectric breakdown of good polymer insulators. Nevertheless, one can consider that the nature of the dielectric material should be carefully chosen, for sustaining the Efield. This situation corresponds to figure 2a.

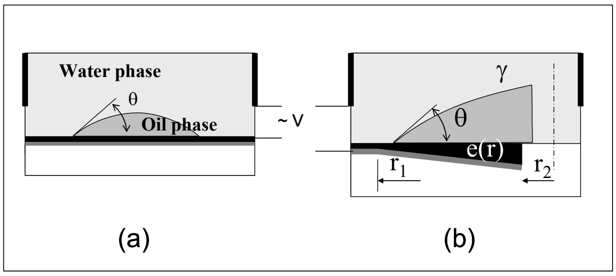


Figure 2: Electrowetting situation (a) "normal" planar geometry. (b) radial gradient of dielectric thickness allowing the centering of the liquid drop.

On figure 2b one uses the same principle for the drop actuation, but one builds a radial gradient of the dielectric thickness: e(r) , where "e" the thickness now depends on radius "r". In this situation there are two main differences compared to the "normal planar geometry.

The dependency of the contact angle versus voltage is modified. The figure 3 for instance shows the expected evolution of the contact angle versus voltage, with and without the thickness gradient.

The figure 3 has been calculated using the modified formula:

$$\cos(\theta)=\cos(\theta_0)-1/2\ \varepsilon\varepsilon_0 /\ (e(r)\gamma)\ V^2. \qquad (2)$$

where r is the radius of the drop base in contact with the solid surface. For Figure 3 calculations, one considers a gradient where r_1=3mm, $e(r_1)$=1,3µm, r_2=2,5mm, $e(r_2)$=4µm.

The second consequence of installing the gradient is the centering of the drop, which is the expected effect. One can estimate the strength of this effect by applying the following calculation:

If we suppose that the drop is off-centred by a distance "s", then the excess electrostatic energy of the off-centred drop is approximated by (assuming $s \ll r_0$ the drop radius):

$\Delta E = 1/2\ \varepsilon\varepsilon_0\ V^2\ r/e^2\ |de/dr|\ s^2$ (3)

"r" is the drop radius and de/dr is the gradient of thickness. This calculation gives only an order of magnitude and should be taken as a rough estimate. Nevertheless, if one plugs reasonable orders of magnitude, one can obtain the equivalent "spring" constant for the mechanical centering, which would be defined as

$\Delta E = 1/2\ K\ \ s^2$ (4)

K Would be estimated as K ~ 0,1 N/m

There is no friction force to compare to K at this stage, rather this value will be useful for relative comparisons.

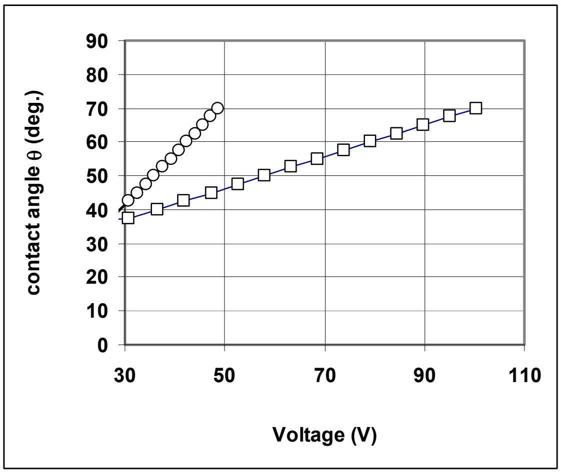


Figure 3: electrowetting curves with gradient (squares) or without gradient (circles). The electrowetting response is lower with the gradient, as the relevant dielectric thickness, at the wetting contact line, increases with voltage.

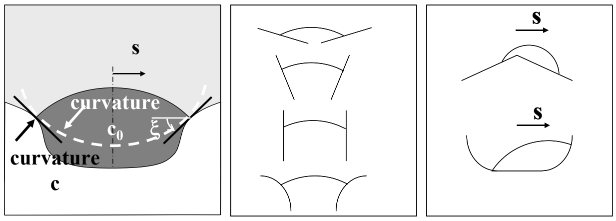
Centering by the geometry

We now consider that the liquid drop is deposited into a cavity with arbitrary shape with full rotaional syetry around optical axis.

In this configuration (see Figure 4) , using a 2D simplified model, the excess energy of the drop can be shown to be given by:

$\Delta E = (c_0 - c)\ \gamma\ r\ \sin\theta\ \ s^2$ (5)

Where c is the local curvature of the surface at the point of contact of the drop, c_0 is the curvature of the tangent sphere on the contact points (shown as a dashed line on Fig 4), γ is the liquid-liquid interfacial tension, θ is the contact angle of the drop on the surface (material property) and r is the drop radius. The curvatures are counted positively if directed towards the interior of the cavity, for instance in the particular case of the fig. 4a geometry, $c_0>0$. Eq. 5 is an exact result in the simplified 2D model. The Eq. 5 shows that a solid surface which curvature is outside of the tangent sphere will produce stable centering mean of the liquid drop, whereas the surfaces which are inside the tangent sphere will give unstable drops.



a b c

Figure 4: (a) general stability analysis of the drop center, on a given surface. The surface is assumed to have a full rotational symmetry around the vertical axis (optical axis). The tangent sphere curvature c_0 is counted positively on the figure, whereas the curvature of the real supporting surface "c" is counted negatively. (b) examples of surfaces which are self-centering the drop, according to Eq. (5): conical recess, cylindrical hole, toroidal cavity etc… . (c) Examples of surfaces on which the drop will be unstable (non self centering).

In the case of a conical recess, the situation for the drop is to be always stable at the centre whatever the contact angle θ. The energy of an off-centred drop is then given by

$\Delta E = 2\ \gamma\ \ \sin\xi\ \sin\theta\ \ s^2$ (6)

where ξ is the cone angle (see fig. 4 for definition), and the equivalent spring constant can also been estimated as K ~ 0,2N/m for a 45° cone angle.

Other centering means

The calculations above show that dielectric gradient and geometry centering can have roughly the same strength, bringing similar lens quality.

There are a number of other conceptual ways of achieving the centering of the liquid drop. One could think of any gradient in the system, which would affect the liquid liquid interface, assuming this gradient has the right direction. Also electrode edge effects can produce such gradients. Similar effect has been used in liquid crystal lenses recently[9].

Geometries could also vary a lot: according to the formula of Eq. 5, one could use several kind of surfaces, conical with any cone angle: Eq. 6 shows that whatever the cone angle ξ, providing it is a cavity (ξ>0), the cone will make a stabilization of the drop. At the limit of the cone angle $\xi = \pi/2$, the shape would then be a piece of cylinder. More complex shapes could be also chosen as toroidal structures etc…Figure 4 (b) and (c) shows examples of suitable and not suitable surfaces respectively.

4. EXPERIMENTAL RESULTS

On Figure 5, one can see an experimental measurement on an actual lens made with an parylene layer 5 µm thick. The experimental points are shown, recorded during a cycle.

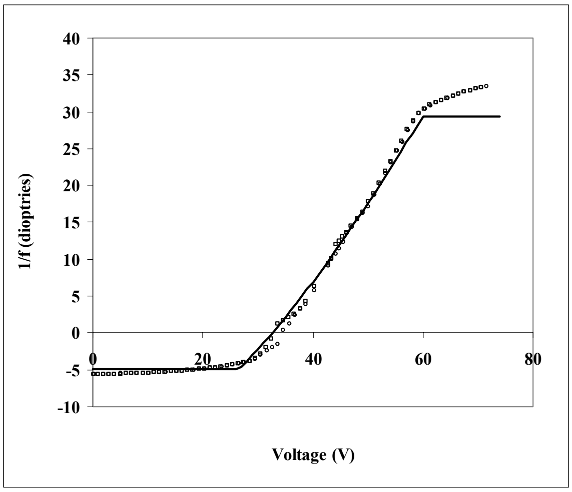


Figure 5: optical power of the lens (1/f) versus the ac applied voltage V. The continuous line corresponds to the modelization of Eq.

It can be seen on figure 5 that there is very little hysteresis.

On the Figure 6, one shows measurements of the stability of the optical axis: a laser beam is focused through the liquid lens, and the XYZ position of the focus point is shown: X and Y as a function of Z.

It can be seen that the centering effect (in this case due to the conical geometry) is working very efficiently: The slope of curves on figure 6 is due to misalignment of the translation stages compared to the optical axis: the important information in Figure 6 is the error compared to the dashed line. This error is of the order to 50µm maximum across the whole 15mm variation of the Z position.

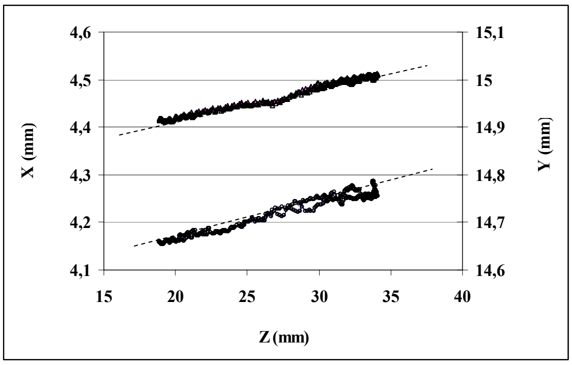


Figure 6: XYZ position of the focus of a laser beam passing through the lens, during a voltage cycle: at V=0, Z=34mm, Z decreasing when voltage increases.

5. CONCLUSIONS

The principle of electrowetting liquid lenses has been shown and some example of particular configurations have been demonstrated. It has been shown that the need of stabilizing the optical axis can be achieved by centering the liquid-liquid interface. Experimental results confirm that the centering effect is effective and that the lens can be used as an optical element in a more complex system.

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