Eur. Phys. J. E **3**, 159–163 (2000)

THE EUROPEAN
PHYSICAL JOURNAL E
EDP Sciences

Variable focal lens controlled by an external voltage: An application of electrowetting

B. Berge[a] and J. Peseux

Laboratoire de Spectrométrie Physique (UMR Université Joseph Fourier-CNRS, 5588) B.P. 87, 38402 St Martin d'Hères, France

Received 1 December 1999

Abstract. We use electrocapillarity in order to change the contact angle of a transparent drop, thus realizing a lens of variable focal length (B. Berge, J. Peseux, Patent deposited in Grenoble France, October 8th 1997, numéro d'enregistrement national 97 12781). The key point is the application of gradients of wettability, which control the shape of the drop edge, in our case a centered circle of variable radius. The quality and reversibility of the lens are surprisingly good. The optical power variation can be 5 to 10 times the one of the human eye, for a comparable diameter, with a typical response time of 0.03 s and a dissipated power of a few mW.

PACS. 68.45.Gd Wetting – 42.15.Eq Optical system design – 68.10.-m Fluid surfaces and fluid-fluid interfaces

1 Introduction

Studies about electrocapillarity started in 1875 when G. Lippmann [1] explained the shape variations of a mercury droplet immersed in an electrolyte, when a voltage is applied across the liquid interface. Froumkine [2] applied the same idea to *electrowetting*, or how electric charges at an interface do modify the contact angle of a drop of electrolyte on a metal surface. More recently, clever experiments on self-assembled monolayers on gold surfaces did show how the functionalization with electro-active groups (ferrocene) could amplify such phenomena [3,4]. Actuators and optical switches were tested using mercury drops [5–7]. Recently it was realized that when inserting an insulating film between the electrode and the electrolyte, electrowetting induces large effects, modifying the contact angles by more than 50°. It was established that electrowetting effects are proportional to V^2/e [8]. The variation of wettability is reversible in a very large range of contact angles [8–11]. We present an application of this effect, where we use the drop as an optical lens. Changes of the contact angle of the drop induce changes of the radius of curvature of a liquid-liquid interface, changing its resulting focal length.

Two key points make this principle working: i) Easiness of inducing wettability gradients using electrowetting. ii) Couples of liquids (water/oil) exhibiting small contact angle hysteresis.

Many optical systems allow the focus and magnification to be mechanically adjustable. Nevertheless one may desire active systems without mechanical motion, either for reduced space/price considerations, or for speed. Numerous solutions have been proposed by injecting fluids in a deformable transparent chamber, requiring an external pump [12]. More recently, the high birefringence of liquid crystals [13] was used to build micro-lens arrays, limited to very small lens sizes. Electro-optic materials have also been used for making variable-power 2D lens in a thin film, for opto-electronic applications [14]. The alternative presented here could fullfill the need for adjustable optical systems without mobile parts, in the 0.1-to-10 mm size range approximately. Surprisingly, our results show high quality, speed and reversibility, opening the possibility of fabricating cheap electrically controllable lenses.

2 Principle and realization

Figure 1a is a schematic representation explaining the principle of operation of the liquid lens. A cell contains two non-miscible liquids, one is insulating and non-polar $\boxed{1}$, the other is a conducting water solution $\boxed{2}$. The liquids are transparent with different index of refraction, but with the same density, such that gravity does not deform the liquid-liquid interface, which remains spherical whatever the orientation of the cell. The insulating liquid has the shape of a drop in contact with a thin insulating window (in gray in Fig. 1a). The window's surface is hydrophobic, so that naturally the insulating liquid will sit on it. A transparent electrode is deposited on the external side of the window, we call it the counter-electrode. Application of a voltage between the counter-electrode and the conducting liquid favors the wettability of the surface by

---

[a] *Present address:* Laboratoire de Physique de l'Ecole Normale Supérieure de Lyon, 46 Allée d'Italie, 69364 Lyon cedex 07, France. e-mail: `bruno.berge@ens-lyon.fr`

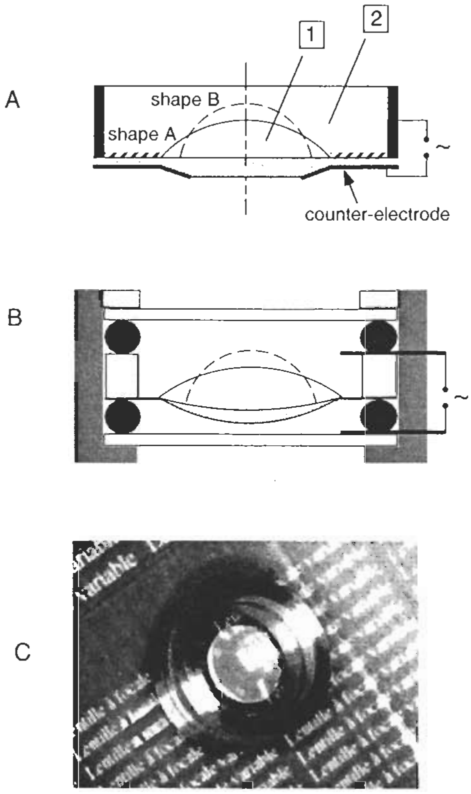

Fig. 1. (a) Schematic representation of the system, not to scale. The cell is filled with water $\boxed{2}$. A drop $\boxed{1}$ of an insulating and non-polar liquid is deposited on the bottom wall, which is made of an insulating and transparent material, in gray. The central disc on the bottom wall surface is hydrophobic, in order to trap the drop. The outer zone, hatched in the figure, is hydrophilic. The optical axis is shown as a short-long-dashed line. (b) Our particular realization of the variable lens. The light gray part is made from a transparent solidified resin, embedded between two stretched polymer films (see text). The voltage is applied between the two liquid compartments, the bottom one being the counter-electrode. The cell is sealed by o-rings. The central part has a diameter of 5 mm. Another version, more compact, uses glue instead of o-rings, for making permanent samples. (c) Photograph of one sample: the diameter of the stainless steel outer case is about 12 mm and the oil drop can be seen as white at the center of the case.

this same liquid. This deforms the interface from shape A to shape B (Fig. 1a) and thus changes the focal length. A simple transcription of a calculation presented in reference [8] enables to establish the expected variation of the contact angle θ of the insulating drop (see Note [15]):

$$\cos(\theta) = \cos(\theta_0) - \frac{\epsilon\epsilon_0}{2e\gamma}V^2\,, \qquad (1)$$

where θ_0 is the natural contact angle at zero voltage, ϵ and e are the insulating wall thickness and dielectric constant, respectively, γ is the surface tension of the liquid-liquid interface and V the applied voltage.

In addition to this general principle, we added the following improvements: i) In order to maintain the drop in the shape A when no voltage is applied, the surface of the wall in contact with the drop has to be treated to be hydrophilic outside of a disc corresponding to the base of shape A in Figure 1a. The hydrophilic zone is hatched in Figure 1a. ii) When the electric voltage is applied, the drop should stay centered on the optical axis. For this purpose, we use for the wall an insulating film of variable thickness $e(r)$, r being the distance to optical axis, see Figure 1a. The thickness gradient is radial and directed towards the optical axis. It induces a gradient of wettability of the surface, due to the variable electrowetting effect as seen from equation (1). This gradient has two beneficial consequences: First it imposes a circular base for the drop, avoiding optical distortions. Second, it centers the drop on the optical axis.

We have chosen a simple way to realize prototypes of this variable-power lens, although more sophisticated variations are allowed. As depicted in Figure 1b, we used stretched polymer films as the basis for the insulator wall on which the drop is attached, the counter-electrode being another liquid compartment filled with salted water (bottom compartment in Fig. 1b). We first make the thickness gradient by fabricating [16] a thin transparent lens made from epoxy, trapped between two stretched polymer films (in gray in Fig. 1b). The surface of the top polymer film is naturally hydrophobic, and it is chemically treated to become hydrophilic outside the central part. An external stainless steel ring is glued for mechanical integrity, and the whole cell is assembled in salted water (conducting liquid). A drop of about 15 μl of the insulating liquid is injected with a syringe, before closing. For the conducting liquid, we used a solution of Na_2SO_4 in water. We also add poly-ethylene-glycol when the viscosity needs to be tuned. The insulating liquid can be almost every organic non-polar liquid, non-miscible with water. We used 1-bromo-dodecane, having the same density as a solution of a few percent of Na_2SO_4 in water. Chloro- or bromo-naphtalene, silicon oil, etc. work also very well. Mixtures of these chemicals are also possible in order to reach the desired properties for the two liquids: densities as close as possible; indices of refraction as different as possible; low melting points; adapted viscosity. Figure 1c shows a photogrtaph of one cell, where sealing is obtained with glue.

3 Characterization

We measure the focal length by using the set-up of Figure 2a. We use the variable lens as a magnifying glass. From the apparent magnification of a grid object, one deduces simply the value of the focal length. We checked that the values of the focal length measured by this technique coincide with the one obtained using classical methods. This method is crude but sufficiently precise for our purpose, considering the large optical power variations achieved. Figure 2b presents images of the grid (pitch of 130 μm), the lens at rest is shown on the left, under 210 V on the right. Figure 3 shows an example of the variation of the inverse focal length, in dioptries, as a function of the applied voltage. At our precision the reversibility is almost

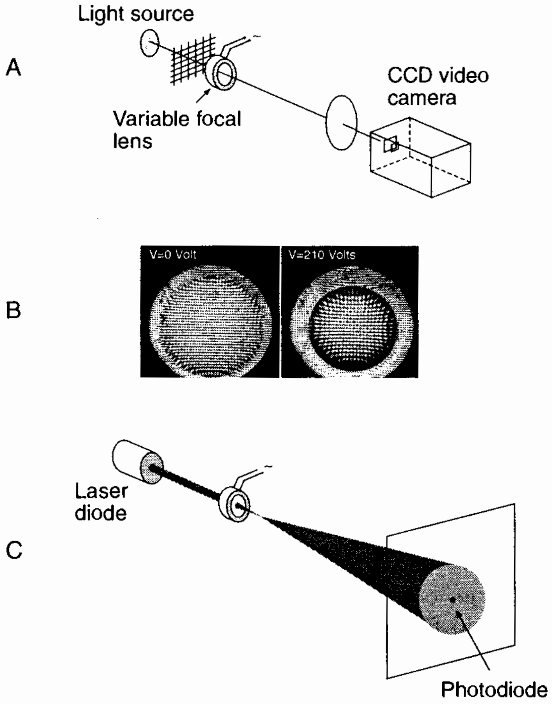

Fig. 2. Experimental arrangements for measuring the lens properties: (a) The focal is deduced from the magnification of a grid placed behind it. (b) Typical pictures of the grid under 0 V and 210 V. Similar distortions would also be observed with a normal glass lens, and their correction would require a multi-element optics. (c) Fast (relative) measurement of the focal length: a small silicon photodiode measures the intensity at the center of the beam spread by the focusing through the variable lens. The recorded intensity thus depends on the focal length. A computer samples the signal every 0.1 ms.

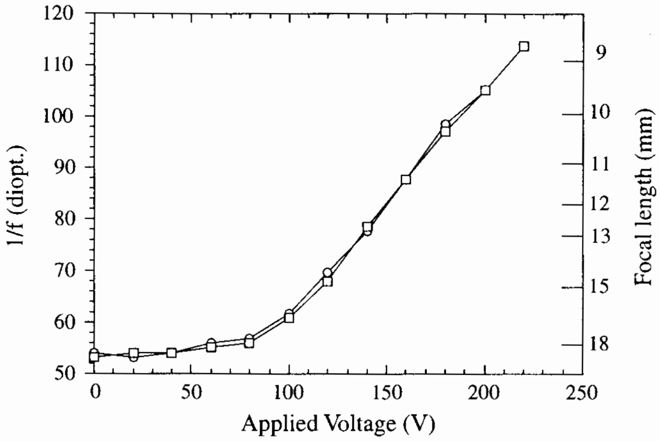

Fig. 3. Inverse focal length of a particular lens of 6 mm diameter, filled with *α-chloronaphtalene* as the insulating liquid, and a Na_2SO_4 solution in water, as a function of voltage. The two curves which correspond to increasing (○) and decreasing (□) voltage, are superimposed.

perfect, as the curve obtained when decreasing the voltage is exactly superimposed on the increasing one. One observes that the power of the lens is stable below 90 V, and starts to raise above this voltage. Then a large focal length variation is observed, here about 60 dioptries. The higher limit of our mesaurements (Fig. 3) corresponds roughly to a contact angle of 90 degrees (estimated from the size of the drop, knowing the quantity of oil in the drop). Although it is thinkable to use the lens at higher voltage, it might be useless, as large optical aberrations are expected (see Fig. 2b). Depending on the exact configuration, the inverse focal variation ranges from 30 to 100 dioptries for 200 V applied. Although the applied voltages are quite high, the electrical power dissipated in the system is very small: We used a 1 kHz frequency, the sample behaving as a simple capacitor of 50 pF capacitance and a loss factor of about 0.05. The dissipated power is a few mW at 250 V, such that it is possible to use a very small power supply, safe for health. It is difficult to deduce an accurate prediction for the focal length *versus* voltage, as it is very sensitive to the precise epoxy lens shape, but the order of magnitude is coherent with measurements. One can understand why the focal length starts only to vary above a threshold voltage (about 80 V in Fig. 3): if the hydrophilic zone did not exist, the drop would spread largely under zero voltage, and its diameter would be much larger. The focal length would then vary continuously from zero voltage. The first part of the curve corresponds thus to the drop being constrained by the treated hydrophilic zone.

The whole set-up of Figure 2a is mounted on an optical rail which can be rotated in every orientation with respect to vertical. We captured images of the grid comparable to Figure 2b in different orientations of the lens, from vertical to horizontal. A numerical subtraction of different images, pixel by pixel, did not show any detectable distortion.

Figure 2c shows the set-up for recording the fast response of the lens. The beam of a laser diode is focused by the variable lens. A small pin silicon photodiode is placed in the trajectory of the beam, well behind the focal plane of the lens. The focal length variation changes the size of the spot on the screen, such that the intensity recorded in the pin photodiode placed at the spot center is varying. Usually we apply a voltage step to the lens, the response signal being related to the focal length. Figure 4 shows typical recordings of intensity *versus* time after a voltage step, for a lens of 2.5 mm diameter. We see that for fluids having low viscosities of a few cS (squares in Fig. 4), the response compares to a damped harmonic oscillator. Here the period of oscillations is $T = 25$ ms. Increasing the viscosity of one of the two liquids by additives to about 40 cS (circles in Fig. 4), makes the response faster, with an exponential decay of 15 ms time constant. In principle, if one is able to tune the viscosity to be at critical damping, one should theoretically get an exponential response with a time constant of $T/2\pi$ (about 4 ms in this case). Practically we rarely get a pure exponential response and the real response time is longer than this value by a factor of two to four. Of course if the viscosity is too high, overdamping slows down the response dramatically. When the drop liquid is more viscous than the surrounding liquid, upon quick receeding meniscus a thin liquid film is left. It then forms very small droplets, which undergo a force

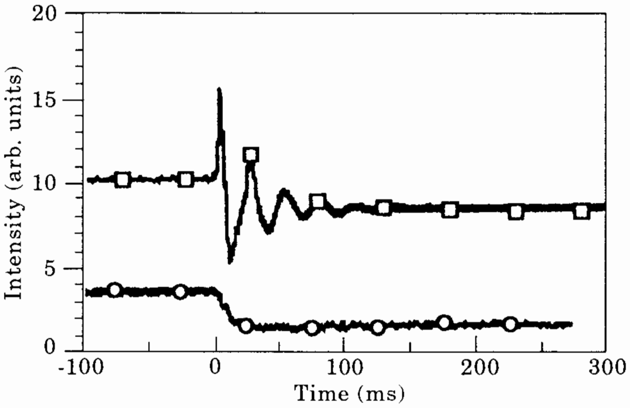

Fig. 4. Time response of a 2.5 mm diameter lens, after a voltage step from 0 to 300 V, applied suddenly at $t = 0$. The squares correspond to 3% Na_2SO_4 solution in water, the drop being 1-bromo-dodecane. The circles correspond to the same sample, poly-ethylene glycol being added to the water solution, increasing its viscosity to about 40 cS.

towards the central drop due to the wettability gradient induced by the electric field combined to the dielectric thickness gradient. It then appears more advantageous to damp the oscillations by making the water-based fluid more viscous, rather than the drop liquid. In order to check for the reversibility, we could apply up to 10^6 cycles from zero to maximum voltage without noticing any difference with the behavior of a fresh sample.

4 Discussion

4.1 Why does it work well?

The first question one should address about the effect presented here is: Why does it work so well? Wetting phenomena are usually hysteretic and tremendous efforts are needed to get surfaces with less than 5° of contact angle hysteresis between advancing and receding meniscus on the surface. The source of hysteresis usually comes from the trapping of the wetting line by defects [17,18], resulting in irregular shapes for drops. Here we measure almost no hysteresis, within the accuracy of our experiment. We suggest that it comes from the above-mentioned thin liquid film left behind the moving meniscus. It means that the line of attachment of the liquid interface on the solid never detaches from its initial position, thus suppressing friction in the system. As a consequence, a relatively small gradient of wettability is able to get the drop stable, circular and centered on the optical axis. From reference [15] one can estimate that in our conditions at $V = 200$ volts the wettability gradient corresponds to an effective surface energy gradient $\frac{\delta\sigma}{\delta x} \simeq$ 10-20 mN/m/mm. Nevertheless, if small irregularities of the wetting line are still present at a spatial scale ξ, it is well known that these distortions die exponentially at distances of the order of ξ, away from the drop perimeter [19]. Thus the central part of the drop has always a spherical shape. Also the energy cost of the residual distortions of the contour line depends upon the contact angle as $\sin^2(\theta)$ [20], such that it is not favorable to work at small θ. Practically we always start with contact angles $\theta \simeq 45°$ at zero voltage, this angle being adjusted by the oil volume that is injected in the drop.

4.2 Size limitations

For making large-size lenses, the difficulty comes from distortions induced by gravity if the accuracy of the density matching is insufficient. Assuming a residual difference $\Delta\rho$ of liquid densities, between two points at the liquid-liquid interface the local curvature depends on their height difference Δh as

$$\Delta C = \frac{\Delta h}{\lambda^2}, \qquad \lambda = \sqrt{\frac{\gamma}{\Delta\rho g}}, \qquad (2)$$

where C is the local curvature and λ is the capillary length, γ is the liquid-liquid interfacial tension and g is the gravity acceleration. In equation (2) Δh can be at most equal to the lens diameter, when this one is vertical. The lens diameter should thus always be much smaller than λ. If one adjusts the liquid densities to an accuracy of about 10^{-3} g/cm^3 easy to get and to keep over a large temperature range, assuming an interfacial tension of about 40 mN/m, one gets a capillary length $\lambda \simeq 7$ cm. We did fix the diameter of the lens to be 5 mm max, then the distortions induced by gravity produce variations of the focal length f of the order of $\Delta f/f \simeq$ a few 10^{-3} across the lens full aperture. Depending on the particular application, this size limit can be more or less severe, but it is clear that one could probably increase the lens diameter up to 20-30 mm without too many difficulties. Of course the response time would be slower, of the order of 1/10 s. While using the 5.4 mm diameter lenses as a CCD objective, we did not observe any problem with vibrations of the liquid. Of course when increasing the size, drop vibration could become a more severe problem. For making small-size lenses, it seems that there is no clear limit. Production of thickness gradients seems easy, as routine production of microlens arrays exist, using microlithography, sol-gel or excimer techniques [21]. It could also be interesting to test the feasibility of active mini-lens arrays.

5 Conclusion

The concept shown in this paper can be open to various designs. We have used a thickness gradient for centering the drop under electric voltage, but dielectric constant gradients, or permanent wettability gradients, could be used. One could also think of multiple transparent electrode designs, where the mutual capacitance between electrodes creates automatically the desired voltage gradient. Also electrodes addressed individually can produce discrete focal length variations, then relaxing the tolerance about the quality of the surface supporting the drop. It is also possible to think about centering the drop by a suitable choice of the geometry of the surface on which the drop is attached (a conical depression for instance might produce the centering effect very economically). The wettability gradients can be used also to build adaptative cylindrical lenses, or even prisms of variable deviation. It is not possible to cite all potential applications. All imaging systems requiring fast zoom or fast focusing could use this lens. Endoscopy could benefit from the compactness of the lens, which could be not much bigger than a usual glass lens. In optical reading heads the mechanical feedback which is used to keep the laser focussed on the tracks might be upgraded by our invention, etc.

Nota Bene: a former publication [22] reports the use of electrowetting for controlling the shape of liquid lenses but with limitation to very small lenses.

We deeply thank Denis Leroux, University Joseph Fourier Grenoble I, for his constant support of the project. We thank also Prof. M. Vallade and Prof. J. Lajzerowicz for numerous interesting discussions.

References

1. G. Lippmann, Ann. Chim. Phys., cinquième série **5**, 494 (1875).
2. A. Froumkine, Actual. Sci. **373**, 1 (1936).
3. J.A.M. Sondag-Huethorst, L.G.J. Fokkink, J. Electroanal. Chem. **367**, 49 (1994), and references cited therein.
4. J.A.M. Sondag-Huethorst, L.G.J. Fokkink, Langmuir **10**, 4380 (1994); see also J.A.M. Sondag-Huethorst, Thesis 1994 (CIP-Gegevens Koninklijke Bibliotheek, den Haag, The Netherlands).
5. E. Colgate, H. Matsumoto, J. Vac. Sci. Technol. A **8**, 3625 (1990).
6. J.L. Jackel, S. Hackwood, J.J. Veselka, G. Beni, Appl. Opt. **22**, 1765 (1983), and references cited therein.
7. M. Sato, IEICE Trans. Commun. **E77-B**, 197 (1994).
8. B. Berge, C. R. Acad. Sci. Paris **317**, Sér. II, 157 (1993).
9. M. Vallet, B. Berge, L. Vovelle, Polymer **37**, 2465 (1996).
10. M. Vallet, B. Berge, M. Vallade, Eur. Phys. J. B **11**, 583 (1999).
11. W.J.J. Welters, L.G.J. Fokkink, Langmuir **14**, 1535, 1538 (1998).
12. R. Graham J. Opt. Soc. Am. **30**, 560 (1940).
13. L.G. Commander, S.E. Day, C.H. Chia, D.R. Sylvia, EOS Topical Meetings Digest Series **5**, 72 (1995).
14. M. Yamada, M. Saitoh, H. Ooki, Appl. Phys. Lett. **69**, 3659 (1996).
15. Note the sign, opposite to reference [8], due to the choice of θ being the contact angle of the insulating liquid (in Ref. [8] θ was chosen as the contact angle of water).
16. A commercial transparent polymer film (SARAN, Dow Chemical, thickness 12 μm) is stretched on the flat extremity of a brass cylinder having a hole of 5.4 mm diameter in its center. By a controlled aspiration of air through the other side of the hole, one obtains a depression of the polymer film, with a radius of curvature around 50 mm. One fills this depression with a transparent liquid resin and one covers it with a second stretched polymer film, a commercial fluorinated transparent polymer film (Dupont AF1600, 12 μm thick). One then increases the aspiration such that both films are under tension, providing smooth surfaces. After solidification of the resin, one obtains the lens shape for the epoxy embedded between both polymer films.
17. A.W. Adamson, *Physical Chemistry of Surfaces*, 5th edition (John Wiley and Sons, 1990), Chapt. X.
18. P.G. de Gennes, Rev. Mod. Phys. **57**, 827 (1985).
19. J.F. Joanny, P.G. de Gennes, J. Chem. Phys. **81**, 552 (1984).
20. M.O. Robbins, J.F. Joanny, Europhys. Lett. **3**, 729 (1987).
21. M. Hutley, R. Stevens, D. Daly, Phys. World **July**, 27 (1991).
22. C.B. Gorman, H.A Biebuyck., G.M. Whitesides, Langmuir **11**, 2242 (1995).