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Citation for published version (APA):
Kuiper, S., & Hendriks, B. H. W. (2004). Variable-focus liquid lens for miniature cameras. *Applied Physics Letters*, *85*(4), 1128-1130. https://doi.org/10.1063/1.1779954

DOI:
10.1063/1.1779954

Document status and date:
Published: 01/01/2004

Document Version:
Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

Variable-focus liquid lens for miniature cameras

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(Received 1 March 2004; accepted 2 June 2004)

The meniscus between two immiscible liquids can be used as an optical lens. A change in curvature of this meniscus by electrowetting leads to a change in focal distance. It is demonstrated that two liquids in a tube form a self-centered lens with a high optical quality. The motion of the lens during a focusing action was studied by observation through the transparent tube wall. Finally, a miniature achromatic camera module was designed and constructed based on this adjustable lens, showing that it is excellently suited for use in portable applications. © *2004 American Institute of Physics*.
[DOI: 10.1063/1.1779954]

In most manmade optical systems focusing is achieved by lens displacement. Miniaturization of such systems is complicated regarding fabrication and assembly of the tiny components. Moreover, a fundamental effect arises: the surface-to-volume ratio increases and with that the significance of friction. This effect makes it difficult to downscale devices with moving parts. In contrast, the increasing surface-to-volume ratio can become an advantage if surface-related forces are employed[1] for the focusing action. One option is electrowetting, where the interfacial tension between a solid and a liquid is electrostatically controlled. Recent work concentrates on the use of electrowetting to influence the shape of a drop of liquid and with that its optical properties.[2–4] However, it appears difficult to center the laterally unstable drop around the optical axis. In Ref. 5 it is described how two immiscible liquids in a capillary can be pumped by electrowetting, i.e., by changing the curvature of their meniscus with a voltage. Here we demonstrate that this meniscus can act very well as a lens with adjustable focal length and without the abovementioned centering problems. In contrast to conventional focus systems, the performance of this variable lens improves upon miniaturization. In this report we describe various aspects of such a lens and focus on its use in portable applications such as camera phones.

Figure 1(a) shows a schematic cross section of our variable lens. The cylindrical housing contains two immiscible liquids with different refractive indices. One of the liquids is electrically conducting, for example an aqueous salt solution, the other is insulating, for example a nonpolar oil. If both liquids have equal densities the shape of the meniscus is perfectly spherical, independent of orientation, and rather insensitive to external vibrations and shocks. We coated a glass cylinder with a transparent electrode in order to study the lens from the side. The inside of the cylinder is coated with a hydrophobic insulator. The counter electrode is in direct contact with the conducting liquid. Application of a voltage between the electrodes [Fig. 1(b)] results in an electric field across the insulator, which effectively lowers the interfacial tension between the conductive liquid and the insulator. The resulting change in contact angle θ of the conducting liquid with the wall can be described by

$$\cos\theta = \frac{\gamma_{wi} - \gamma_{wc}}{\gamma_{ci}} + \frac{\epsilon}{2\gamma_{ci} d_f} V^2, \tag{1}$$

where ϵ is the dielectric constant of the insulating film, d_f its thickness, V the applied voltage, γ_{ci} the liquid/liquid interfacial tension, γ_{wc} the interfacial tension between the wall and the conducting liquid, and γ_{wi} between the wall and the insulating liquid. For several combinations of liquids and coatings applies $(\gamma_{wi} - \gamma_{wc})/\gamma_{ci} < -1$, which results in an off-state contact angle of 180° and the presence of a threshold voltage for moving the meniscus. Equation (1) can be used to derive an expression for the dioptric power $\mathcal{D}$ of the meniscus for a cylinder radius R and refractive indices n_i and n_c for the insulating and conductive liquid, respectively,

$$\mathcal{D} = \mathcal{D}_0 + \frac{\epsilon(n_i - n_c)}{2\gamma_{ci} d_f R} V^2 \tag{2}$$

with $\mathcal{D}_0$ the dioptric power in the off-state. For a 3-mm-diameter lens we can control the dioptric power between −100 and +50 diopters. This range is much wider than

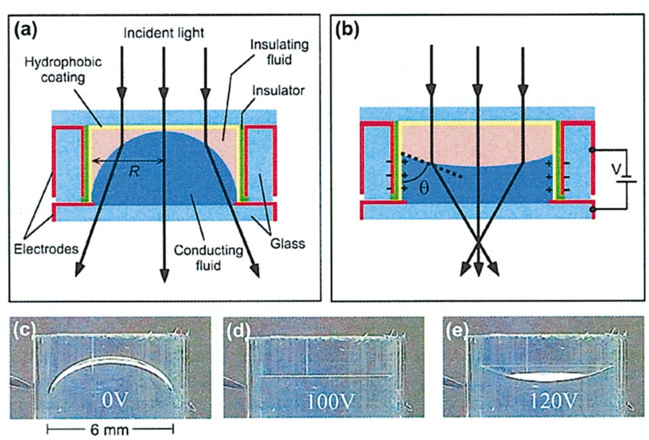

FIG. 1. (Color) (a) Schematic cross section of a liquid-based variable lens in a cylindrical glass housing. The transparent electrodes are formed of 50-nm-indium tin oxide, the insulator is a 3-μm-parylene-N layer, and the 10-nm-hydrophobic top coating is a dipcoated fluoropolymer (AF1600, supplied by Dupont). The top and bottom glass plates are glued onto the glass cylinder with epoxy glue. (b) When a voltage is applied, charges accumulate in the wall electrode and opposite charges collect near the solid/liquid interface in the conducting liquid. The resulting electrostatic force effectively lowers the solid–liquid interfacial tension and with that the contact angle θ. (c)–(e) Video frames of a 6-mm-diameter lens taken at voltages of ~0, 100, and 120 V.

[a)]Electronic mail: stein.kuiper@philips.com the range of the lens in the human eye, which can be varied between +20 and +24 diopters only.

Figures 1(c)–1(e) show three video frames taken at increasing voltage. The meniscus moves smoothly from a convex to a concave position without any sign of hysteresis. The optical quality of the electrowetting lens is strongly related to the radial symmetry of the meniscus. Nonuniformities may for instance be caused by surface roughness or variations in thickness of the insulating coating and give rise to wavefront aberrations. We measured the meniscus shape of the lens in Fig. 1(d) over a diameter of 4 mm using an interferometer and obtained a root mean square optical path length difference of 0.027 wavelengths, showing that the wavefront aberration is well below the diffraction limit.[6]

The environmental conditions for mobile applications can be severe. A camera should operate between −30 and +70 °C and it should survive temperatures between −40 and +85 °C. For the aqueous solution this may lead to freezing problems. The freezing point can be depressed by using a highly concentrated salt solution. In order to keep the density and refractive index low, we use a salt with low atomic mass: lithium chloride. Dissolution of 20% lithium chloride leads to a freezing point below −40 °C, a density ρ of 1.12 $\mathrm{kg/m^3}$ and a refractive index n_c of 1.38. As the insulating liquid we use a mixture of phenylmethylsiloxanes for its high refractive index and good electrowetting properties. A few percent of the dense carbon tetrabromide (ρ=2.96 $\mathrm{kg/m^2}$) is dissolved in the insulating liquid to match the density of the salt solution. The resulting refractive index is 1.55. For both liquids the temperature dependence of the refractive index is approximately equal ($dn/dT=-0.0003/\mathrm{K}$). As a result the effect on the focal length of the lens is small over the required temperature range [see Eq. (2)]. The remaining small change in focal length can be compensated by slightly adapting the voltage.

The lens can be driven by a direct as well as an alternating voltage. We use a direct voltage of typically 50 V to cover the full range required for a camera. This only requires an energy of 0.1 μJ to charge the 100 pF capacitor formed by the wall electrode and the salt solution. A decrease in parylene thickness and interfacial surface tension (e.g., by adding surfactants) lowers the voltage.

An important aspect of variable lenses is the focus speed. We used a 1000 frames per second high-speed camera to study the motion of the meniscus by observation from the side. We applied a voltage step and observed underdamped, critically damped and overdamped menisci by varying the insulating liquid and the cylinder diameter. Critically damped lenses are interesting for use in cameras, since critical damping is the fastest way to react to a voltage step without oscillations. Such oscillations result in a deformed meniscus, which may hinder autofocus algorithms. Figure 2 shows two lenses a few milliseconds after a voltage step: one underdamped (a) and one overdamped (b) lens. The deformed shape in the underdamped lens is clearly visible. We measured the characteristic damping time τ for various liquids and cylinder diameters. In order to find a correlation between the relevant variables d, γ_{ci}, ρ, τ, and the kinematic viscosity ν, we introduce a dimensionless damping time $\tilde{\tau}=\tau\nu/d^2$ and a dimensionless lens parameter $Le=\nu^2\rho/\gamma_{ci}d$. Figure 2(c) shows a graph of $\tilde{\tau}$ and Le for menisci switched from convex (θ=180°) to flat (θ=90°). On a logarithmic scale it appears that the dimensionless damping times for

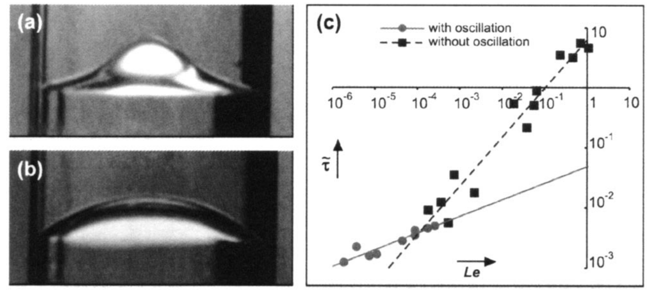

FIG. 2. (a) Video frame showing an underdamped meniscus switching from curved (θ=180°) to flat (θ=90°), a few milliseconds after a voltage step; (b) overdamped meniscus for identical conditions; (c) dimensionless damping time plotted vs the dimensionless lens parameter for lenses of various size and composition.

oscillating menisci form a straight line (solid). The nonoscillating menisci form a straight line (dashed), but with a different slope. We conclude that around the intersection of both lines the meniscus is critically damped. From this point of intersection (Le_{crit}, $\tilde{\tau}_{\mathrm{crit}}$) we can derive an expression for the critical damping time τ_{crit} as a function of d, γ_{ci}, and ρ:

$$\tau_{\mathrm{crit}}=\tilde{\tau}_{\mathrm{crit}}\sqrt{\rho d^3/\gamma_{ci}Le_{\mathrm{crit}}}\approx 0.3\sqrt{\rho d^3/\gamma_{ci}} \quad (3)$$

and the corresponding critical viscosity ν_{crit}:

$$\nu_{\mathrm{crit}}=\sqrt{Le_{\mathrm{crit}}d\gamma_{ci}/\rho}\approx 0.02\sqrt{d\gamma_{ci}/\rho}. \quad (4)$$

Equation (3) shows that smaller lenses are faster and Eq. (4) shows that in smaller lenses a lower viscosity is needed to obtain critical damping. A typical value for τ_{crit} is 7 ms for a 3-mm-diameter lens at an oil viscosity of 7 cSt. The dependencies in Eq. (3) become understandable if we compare the lens with a damped mass-spring system with mass m and spring constant K. For such a system it is well known that the time constant for critical damping is given by $\tau_{\mathrm{crit}}=\sqrt{m/K}$. This implies that the effective mass in the lens is proportional to ρd^3 and the spring constant proportional to γ_{ci}, which seems very plausible. However, the spring constant of the meniscus appears to be strongly dependent on the contact angle θ. If we calculate the force on the edge of the meniscus and differentiate to its position, we obtain the spring constant of the meniscus:

$$K=2\pi\gamma_{ci}\sin\theta(1+\sin\theta)^2. \quad (5)$$

From Eq. (5) it follows that the spring constant is zero for θ=0° or θ=180°, and reaches a maximum for θ=90°. If we assume that the effective mass of the liquids is not strongly dependent on θ, we can conclude that the meniscus is much faster when it is switched around a flat position than when switched around a curved position. Our observation show that this is indeed the case. The oil viscosity varies strongly with temperature. As a result the meniscus will be overdamped for low temperatures and underdamped for high temperatures. If critical damping occurs at 20 °C the damping time increases by approximately a factor of 10 at −30 °C. The use of non-oily insulating liquids strongly reduces this factor.

In a camera, the lens refracts light of different colors. The dependence of the refractive index of the various materials (dispersion) making up the lens may result in chromatic aberration. The dispersion must be well corrected in order to obtain a high optical quality. Conventional lens systems employ grating structures susceptible to haze, or costly doublet

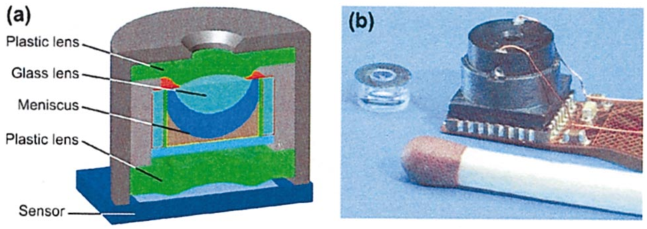

FIG. 3. (Color) (a) Optical design of the camera module containing a liquid lens; (b) the assembled camera module and the liquid lens.

FIG. 4. (Color) Frames taken from a video made with a VGA CMOS camera having (a) a fixed-focus lens and (b) a liquid lens focused at 50 cm and (c) a liquid lens focused at 2 cm.

components for color correction. Liquid-based variable lenses make up a lens system resembling a cemented doublet, making achromatization straightforward. For instance, to make the interface between the liquids achromatic it follows from Eq. (2) that refractive index n and the dispersive power Δ (Ref. 6, also known as the Abbe number) must be related according to $\Delta_i/\Delta_c=(n_i-1)/(n_c-1)$. As we can tune the optical properties of the liquids by mixing or dissolving well-chosen substances, we can make an achromatic liquid lens and avoid the use of costly achromatization methods.

We now describe the design and construction of a camera module for use in a mobile phone. Figure 3 shows a schematic cross section of the module and photographs of the entire camera and electrowetting lens. The height of the lens stack is 5.5 mm measured from the image sensor. The lens has $f/2.5$ and a field of view of 60°. We use a commercially available VGA CMOS sensor (Philips OM6802), having 640×480 pixels with size $5.0\times 5.0\ \mu\text{m}^2$. The entrance pupil diameter is 1.43 mm and the focal length adjustable between 2.85 mm for objects at 2 cm and 3.55 mm for objects at infinity. We position the electrowetting cell between two plastic injection molded lenses. A flat glass plate closes the cylinder on the oil side, whereas a truncated glass sphere mounted on a thin metal diaphragm closes the side of the salt solution. The outer diameter of the cylinder is 4 mm, the inner diameter 3 mm, and the height 2.2 mm. The flexible metal diaphragm compensates part of the mismatch in the thermal expansion between the liquids and the cylinder. The achromatized lens stack has a high optical quality: the camera and observed that it focuses faster than the refresh rate of CMOS sensor. Figures 4(b) and 4(c) show two consecutive frames captured by our camera which was focused between 50 and 2 cm. The measured modulation transfer function (MTF) at 25 line-pairs/mm for an object at 50 cm was 70% across the field [see Fig. 4(b)]. For comparison, a similar image captured with a fixed-focus camera mounted on the same image sensor has MTF value of 80% [see Fig. 4(a)]. The resolution of our camera is maintained after refocusing at a 2-cm-distant object [see Fig. 4(c)]. Note that a hair on the object is clearly visible. For the fixed focus camera the image at 2 cm is blurred. Durability tests show good results as well: we switched the lens over a million times without any decrease in performance and exposed the lens to accelerations of 10^3 times the earth's gravitational constant without any permanent displacement of the liquids.

In summary, we have presented a self-centered liquid-based variable-focus lens having high optical quality. Various properties of the lens have been studied. We demonstrated a miniature variable-focus camera module showing that liquid-based lenses are applicable in many fields of optics where robustness, size, speed, power consumption and durability are critical.

The authors thank L. J. Huijbregts and A. Hirschberg of the Eindhoven University of Technology for their extensive contribution to the work on interface dynamics. They also thank C. J. Renders, M. A. J. van As, J. W. Weekamp, and C. A. N. van der Vleuten for their technical support. The authors gratefully acknowledge B. J. Feenstra, R. A. Hayes, M. W. J. Prins, G. F. A. van de Walle, M. Megens, and J. J. H. B. Schleipen for helpful discussions.

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