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Edited by Hans Zappe and Claudia Duppé
Excerpt
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Part I

Introduction

1 Tunable Micro-optics

Hans Zappe

1.1 Introduction

When considering the structures, fabrication techniques or functionality of miniaturized optics, we see that size does matter. Compared with macroscopic optics, micro-optics is generally manufactured employing different technologies, using different materials, and often relying on entirely different optical effects (Zappe 2012). An upshot of these differences is that micro-optical components and systems may often display functionalities not possible with classical, macroscopic optics. One such functionality is intrinsic tunability, and it is tunable micro-optics that is the subject of this book.

Whereas a macroscopic optical system is usually tuned by a mechanical displacement of components, in micro-optics tunability may often be realized by a controlled change in an intrinsic property of the component itself. Thus the deformation of a soft polymer surface; the change in surface tension of a liquid; or the swelling of surface layers are all mechanisms that may be employed to tune the optical characteristics of micro-optical devices (Friese et al. 2007). The very rich portfolio of effects and materials of which we may take advantage to accomplish tunability is one reason for the broad spectrum of activities in this dynamic discipline.

In this introductory overview chapter, we provide a survey of the current state-of-the-art in tunable micro-optics. Using the established knowledge base in micro-optics as a point of departure (Herzig 1998, Sinziger & Jahns 2003, Zappe 2010), we will look at those micro-optical components whose optical characteristics may be tuned using novel mechanisms inapplicable to macroscopic optics. We have organized the following sections by device, allowing for different tuning mechanisms, and will consider tunable lenses; apertures and irises; filters; and diffractive optics. The chapters which follow will address many of the concepts and devices we present here in greater depth.

1.2 Microlenses

Microlenses are likely to be the optical components most researched and developed with regard to intrinsic variability (Krogmann et al. 2007, Levy & Shamai 2008, Nguyen 2010, Zeng & Jiang 2013). A wide variety of novel actuation mechanisms for tuning the focal length of microlenses is available, due in large part to the fact that unconventional materials, such as fluids and soft matter structures, may be used to fabricate lenses on the microscale. Since these are generally not useful for manufacturing macroscopic lenses, many of the tuning techniques we will consider are thus usually unique to microlenses.

We discuss five general families of tunable microlenses. Three of these are fluid-based concepts, namely liquid lenses, hydraulically tunable fluid-filled membrane lenses, and all-liquid hydrodynamic lenses; the remaining two are deformable elastomeric lenses and liquid-crystal-based lenses. Lenses using these soft states of matter are also the subject of Chapter 3; tunable microlenses are discussed in greater depth in Chapter 5.

1.2.1 Liquid Microlenses

For the first family of fluidic lenses, under the heading of *liquid* microlenses, we subsume those structures which employ only liquids and the interfaces between these for optical functionality. In contrast, *hydraulic* microlenses, discussed in Section 1.2.2, use liquids enclosed in cavities bounded by distensible membranes; *hydrodynamic* microlenses, which we will see in Section 1.2.3, rely on liquid interfaces generated by fluid flow.

Astute observers of nature may have noticed that rainstorms are efficient generators of microlens arrays. The water droplets clinging to a flat windowpane make excellent lenses due to their precise hemispherical profile and extremely smooth water/air interface, dictated exclusively by surface tension. The droplet forms a planoconvex lens, and the curvature of the spherical surface defines the focal length.

Whereas the use of these natural fluid surfaces for lensing in this manner has a long tradition, liquid lenses are of particular interest since they can be tuned. By controllably varying the curvature of the droplet, the focal length may be varied and a tunable lens with no mechanically moving parts (aside from liquid surfaces) results; the relative refractive indices of the lens liquid and the ambient (typically also a liquid) define the refractive power. Numerous means for varying the liquid surface curvature have been employed, and we discuss the most relevant of these in the following sections.

Electrowetting-on-Dielectrics

As is seen in the schematic sketch of Figure 1.1, the curvature of the spherical droplet surface (whether of a liquid in air or of a liquid embedded in a second liquid) is given by the contact angle θ_V [°], which is in turn defined by the surface energies of the boundary between liquid, substrate, and ambient. It was already known in the nineteenth century that θ_V can be varied by applying a bias between the fluid and its surroundings, an effect known as electrowetting (Quilliet & Berge 2001). This effect forms the basis for an important branch of tunable fluidic optics (Krogmann et al. 2008*a*).

It was shown only twenty years ago that a variation of this phenomenon, electrowetting-on-dielectrics (EWOD), allowed controlled variation of liquid contact angles using reasonable (i.e., below 100 V) voltages (Berge 1993). EWOD uses the capacitive arrangement shown in Figure 1.1, in which the liquid droplet is deposited on an insulating dielectric over a conducting substrate. When a bias is applied between the droplet and the substrate, the contact angle θ_V then varies with applied voltage V [V]

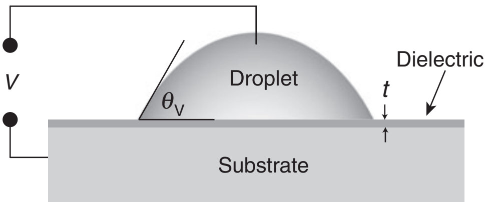

Figure 1.1 For electrowetting-on-dielectrics (EWOD), a liquid droplet is separated from a conducting substrate by an insulating dielectric with thickness t; a voltage applied between liquid and substrate results in a bias-dependent contact angle θ_V. A change in θ_V leads to a change in droplet curvature and thus tuning of the focal length.

according to the Lippmann equation (Krogmann et al. 2006, Yang et al. 2003) as

$$\cos\theta_V = \cos\theta_0 + \frac{\epsilon_d}{2t\sigma_{lv}} V^2 = \cos\theta_0 + \eta \tag{1.1}$$

where θ_0 [°] is the contact angle in the absence of any bias. In the previous expression, t [m] is the thickness of the dielectric layer, ϵ_d [F/m] its permittivity, and σ_{lv} [J/m^2] the interfacial energy between the liquid and the vapor (the ambient surrounding the droplet). We may then define η [ ] as the electrowetting parameter, representing the strength of the electrostatic energy with respect to the surface tension. EWOD has extensively been used for droplet manipulation in microfluidic systems (Kedzierski et al. 2009, Srinivasan et al. 2004) and in displays (Hayes & Feenstra 2003).

When used to tune the curvature, and hence the focal length, of a liquid lens, the contact angle change, due to EWOD given in Equation 1.1, results in a variation of focal length f [m] of the form

$$f(V) = \frac{D}{2(n_L - n_A)\sin\theta_V} \tag{1.2}$$

for aperture diameter D [m] and refractive indices of the lens liquid and ambient, n_L [ ] and n_A [ ], respectively. For practical tunable liquid lens structures, EWOD typically uses a fluid ambient, such that the lens droplet is surrounded by a liquid electrolyte, through which the droplet is then electrically contacted. The lens and ambient fluids are chosen to have densities as closely matched as possible, thereby reducing or eliminating the effects of variable orientation, movement, or vibration (Ren et al. 2010).

Numerous tunable microlens configurations employing EWOD actuation have been demonstrated. Original work employed α-chloronaphthalene as the lens (droplet) liquid and a solution of Na_2SO_4 in H_2O as a density-matched conducting ambient liquid (Berge & Peseux 2000); a focal length change of a factor of 2 was seen for applied voltages exceeding 200 V. Further experiments on planar substrates using indium tin oxide (ITO) electrodes investigated lubrication between lens and substrate, tuning both focal length and position (Krupenkin et al. 2003), and also proposed means for setting a fixed focal length using photopolymerizable droplet materials (Yang et al. 2003).

Important for practical applications of this type of liquid tunable microlens is fabricating the entire structure in a laterally stabilized, sealed package. Using a glass cylinder for mechanical stability, as seen in Figure 1.2, one of the earliest fully

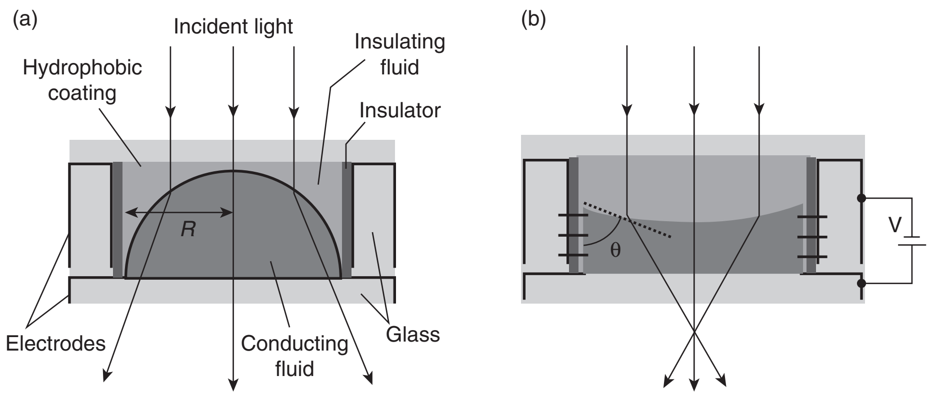

Figure 1.2 A liquid lens system packaged in a glass cylinder; the two electrodes are on the bottom and side surfaces of the cylinder, where the variable contact angle is generated on the side surfaces. From Kuiper and Hendriks (2004).

packaged liquid lenses then employed ITO electrodes coated with parylene, a family of poly(p-xylylene) polymers, as an insulator and a hydrophobic surface coating on the inside surfaces (Hendriks & Kuiper 2004, Kuiper & Hendriks (2004)). Ultimately integrated with a charge-coupled device (CCD) image sensor, the 5.5 mm tall water/oil lens system demonstrated a focus variation between 50 and 200 mm. Concepts for using this lens in an optical zoom system and correcting chromatic aberrations have suggested means for optimizing its optical performance (Kuiper et al. 2005).

An alternative approach for liquid lens stabilization using microsystems fabrication techniques is shown in Figure 1.3 (Krogmann et al. 2006). As seen in the schematic sketch of Figure 1.3a, the structure is based on an etched V-groove structure in a silicon substrate, on which ITO electrodes are deposited. After filling with an aqueous inorganic salt solution, with a density of 2.1 g/cm^3 and a refractive index of 1.51, for the lens and a density-matched perfluorocarbon for the ambient fluid, with refractive index of 1.293, the entire structure was sealed using a pyrex substrate and a glass cover plate.

This lens system allowed tuning of the focal length between 2.3 mm and infinity, with a maximum applied bias of 45 V. Wavefront measurements showed the expected smooth lens surface and close to diffraction-limited performance, with immunity to vibration due to density matching of the two liquids. Variations on this semiconductor-based fabrication technology using SU-8, a high aspect ratio photoresist, have allowed for more variability in the lens positioning structures (Chang et al. 2007). Alternatively, completely planar concepts either use structured multiple electrodes (Liu et al. 2008) or shallow recesses or mesas (Tsai et al. 2009) to position and subsequently tune the lens.

Means have been proposed to separate the electrowetting actuation from the lens itself, to essentially “pump” the lens liquid and thereby change the curvature of a spherical liquid surface pinned into position. Although a greater range of curvatures can be attained (Chang et al. 2012), the concept currently suffers from the fact that the lenses are formed by a fluid/air interface, and are thus sensitive to vibration, movement, and

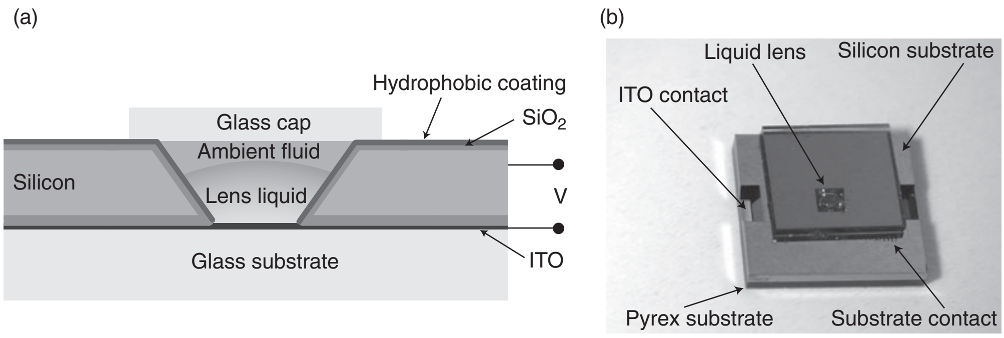

Figure 1.3 A microsystems-based liquid lens system fabricated using silicon and glass technologies. (a) Schematic cross section showing the etched silicon structure for lens positioning bonded to a pyrex substrate, the glass cover and the electrodes. (b) Photograph of the completed $8 \times 8 \times 8$ mm^3 system. Photo courtesy of Florian Krogmann.

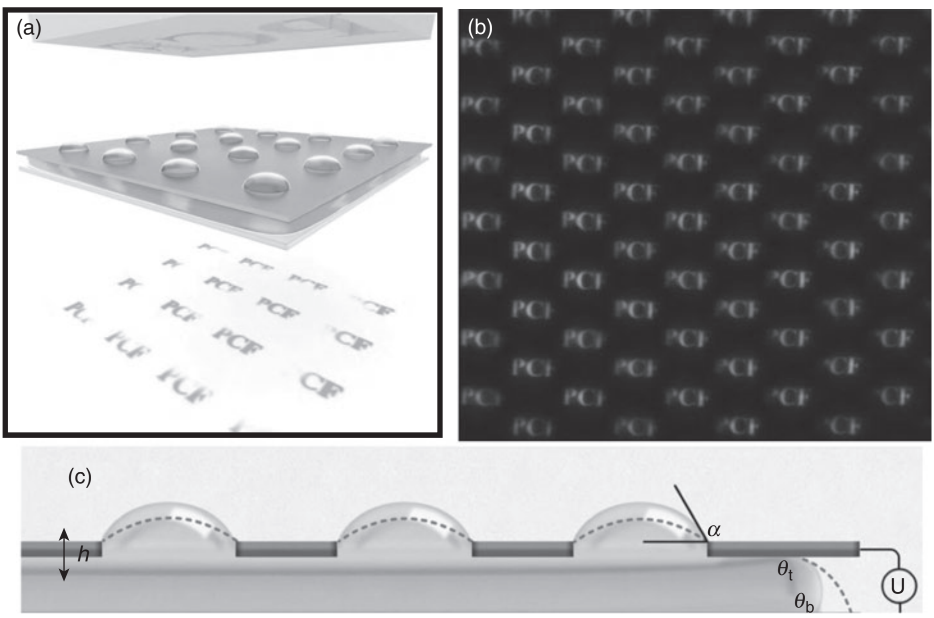

Figure 1.4 A liquid microlens array tuned by electrowetting actuation of the fluid in the reservoir below (panel (c)). Finite imagery of a pattern in panel (a) generates the image shown in panel (b) From Murade et al. (2012).

orientation. This idea has been extended to actuation of liquid lens arrays: Figure 1.4 shows a two-dimensional array of lenses, all actuated from a single liquid reservoir (Murade et al. 2012). Using a water-based fluid, electrowetting actuation changes the pressure in the lower chamber, causing a distension of the lens menisci. The lenses may be tuned in focal length from 2 to 8 mm at frequencies greater than 1 kHz, implying potential for use in tunable array imagers.

Electrowetting-on-dielectrics allows one bit of further flexibility in lens design, namely the realization of reconfigurable two-dimensional tunable lens arrays. Since EWOD is well established as a mechanism for liquid droplet movement, as has been demonstrated in a wide variety of microfluidic systems, the technique may also be used to reposition liquid lenses on a planar substrate (Krogmann et al. 2008*b*). The approach employs a microstructured surface incorporating a rectangular grid structure; this grid provides a mechanism for pinning the edges of a droplet on the surface which may be moved using the forces of electrowetting generated by a buried electrode array. It has been shown that two-dimensional positioning accuracy of 70 μm can be achieved. Using the same electrode configuration, the positioned lenses may also be tuned in focal length, in the range of 0.58 to 1.24 mm.

Dielectrophoresis

An alternative to electrowetting for tunable liquid lens actuation is dielectrophoresis. As we saw above, electrowetting is a surface phenomenon in that the contact angle is varied using an applied electric field; it requires a liquid with suitably high conductivity. In contrast, dielectrophoresis is a bulk effect and requires the use of two nonconducting liquids with differing dielectric constants (Jones 2002). The application of a nonuniform electric field to this pair of liquids results in a movement of the interface due to induced polarization in the dielectric fluids (Gascoyne et al. 2004), so that the dielectrophoretic force F_D is proportional to the gradient of the electric energy and the difference between the dielectric constants of the two liquids (ϵ_A, ϵ_B), or

$$F_D = \frac{\epsilon_0}{2} (\epsilon_A - \epsilon_B) \nabla E^2 \tag{1.3}$$

for electric field E. Particularly since no contact between electrode and droplet is required, dielectrophoresis has also been extensively applied to droplet manipulation in microfluidic systems.

Typical dielectrophoretic systems use concentric rings of electrodes to generate the required field gradients, and while requiring relatively high voltages, power consumption is low since there is no current flow. Individual dielectrophoretic microlenses (Cheng & Yeh 2007) have been successfully demonstrated using two immiscible liquids and a suitably patterned electrode array, as seen in Figure 1.5. For a lens with 3 mm aperture, a focal length tuning range of 12 to 34 mm was demonstrated, although applied voltages of up to 200 V were required. As with all liquids, the refractive index of the fluids used for dielectrophoretic lenses vary with temperature, such that focal length is temperature dependent; optimization of the liquids employed and limiting the temperature ranges can minimize this effect (Zhang et al. 2014).

Dielectrophoresis has also been used to actuate liquid-crystal-based lenses (Cheng et al. 2006*b*) of interest, since liquid crystals have a high refractive index and are not susceptible to electrolysis, a problem for aqueous materials for high electric fields. It has also been shown that dielectrophoretic lenses can be fabricated on flexible substrates (Lu et al. 2013), albeit with relatively slow response times and requiring high voltages.

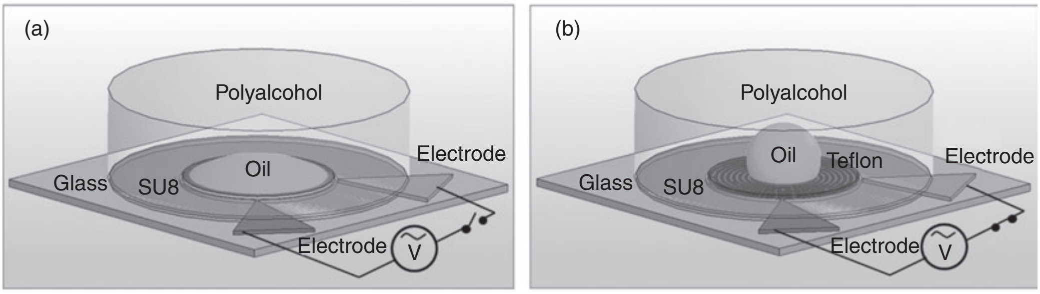

Figure 1.5 A dielectrophoretic liquid lens, consisting of an oil droplet suspended in alcohol, actuated using a structured electrode; droplet size is 500 μm. (a) No applied voltage; (b) actuated. From Yang et al. (2011).

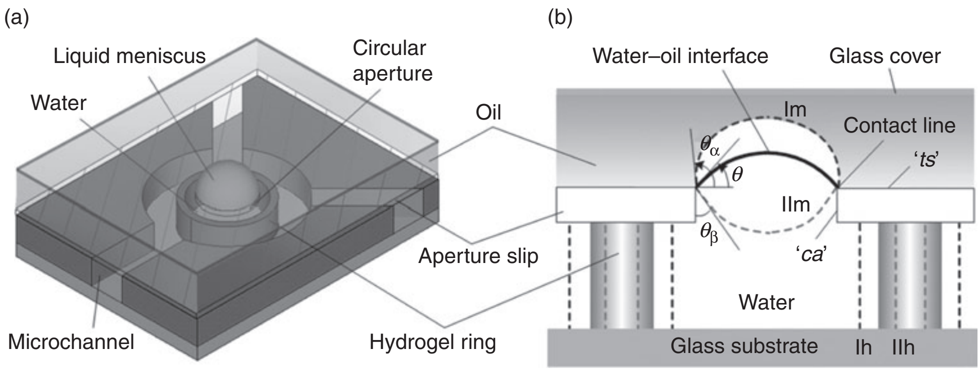

Figure 1.6 An oil/water-based liquid microlens actuated using a hydrogel. The hydrogel in the water-filled chamber absorbs or expels water as a function of temperature, changing the pressure and thus the meniscus shape of the curved oil/water interface. From Dong et al. (2006).

Mechanical Pressure Tuning

A number of mechanical actuation mechanisms, with which the pressure on the lens liquid may be varied, have also been employed for tuning liquid lenses. One useful technique has been the use of hydrogels, part of a family of highly hydrophilic polymer networks which can absorb large volumes of water, thereby undergoing significant expansion. As seen in Figure 1.6, using an immiscible oil/water combination, the pressure increase in a water-filled chamber due to the expansion of a surrounding hydrogel induces a change in the curvature of the water/oil interface and thus the focal length of the resulting convex lens (Dong et al. 2006).

Hydrogel expansion can be stimulated by numerous means, including controlled increase in temperature (Dong et al. 2007), change in pH (Dong & Jiang 2006), or application of infrared radiation (Zeng & Jiang 2008); the technique also allows generation of microlens arrays (Zeng et al. 2010). Alternative approaches for generating the change in liquid pressure leading to a deformation of the liquid meniscus include the use of magnetic actuators and ferrofluids (Xiao & Hardt 2010).

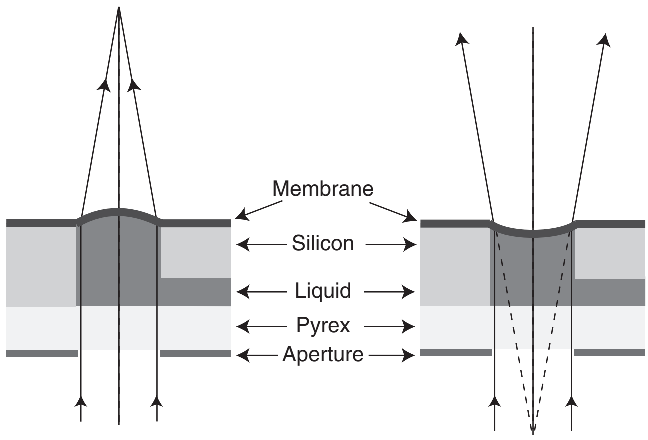

Figure 1.7 Schematic cross section of a hydraulically tunable membrane microlens. Pressure is applied to a liquid-filled microfluidic channel etched into silicon and sealed using a glass substrate and a polydimethylsiloxane (PDMS) membrane; pressure applied to the liquid causes the membrane to distend, forming a convex *left* or concave *right* lens.

1.2.2 Hydraulic Microlenses

A second family of tunable liquid microlenses is that of hydraulically tunable fluid-filled membrane lenses. In contrast to the liquid lenses of Section 1.2.1, hydraulic lenses employ optical fluids fully enclosed in microfluidic systems. As shown in Figure 1.7, the lens may be realized by capping part of the microfluidic chamber with a distensible, optically transparent membrane; by increasing the pressure on the fluid in the chamber, the membrane expands, generating a convex profile, whereas negative pressures yield concave profiles. The lens functionality is still generated by the body of the fluid, but its profile is defined by the distended membrane. Hydraulic or pneumatic actuation[1] has also been shown to be useful for tuning other micro-optical components, most notably micromirrors (Werber & Zappe 2008). Membrane-based microlenses are also the subject of Chapter 9.

The tunable hydraulic lens appears to have been invented several times. Related concepts seem to have been first proposed for use in eyeglasses (Wright 1968) or for underwater acoustic imaging (Knollman et al. 1971) in the late 1960s, but it took a few decades before developments in microtechnology allowed fabrication of functional miniaturized microlens prototypes. An early, relatively large version with a 2.7 cm aperture diameter used a polystyrene membrane and was filled with dimethyl oil (Sugiura & Morita 1993). Pressure was applied using a syringe and, although tunability was demonstrated, gravity effects deformed the profile, limiting its utility. A later 2.0 cm version used polydimethylsiloxane (PDMS) – the material most often used at present – as a thin lens membrane (Zhang et al. 2003), and it was shown that microlens arrays can also easily be realized (Chronis et al. 2003). As seen in Figure 1.8,

[1] We distinguish between hydraulic (liquid pressure) and pneumatic (gas pressure) actuation; most tunable liquid lenses are hydraulically actuated, although some (such as Zhang et al. 2014) are hybrids.