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Abstract

In this paper, we discuss liquid lenses driven by various mechanisms. By properly designing the device structure and choosing the optimal materials, the liquid lenses offer great potential for practical uses. The driving mechanism dictates the application and performance of the liquid lenses. Here we categorize the driving mechanisms into mechanical and electrical ones. In general, mechanical driving with an elastic membrane and an external pump drives liquids in a cavity by controlling the hydraulic pressure. The mechanical driving method can be applied to most of the liquids, but the application of the electrical driving method would be limited by the conductivity or the permittivity of the liquids. Therefore, the properties of the different liquids, e.g., dielectric liquids, liquid crystal molecules, and conductive liquids, deeply affect the mechanism we may choose to realize a liquid lens. Among various electrical methods, dielectrophoresis (DEP), electrostatic forces, and electrowetting-on-dielectric (EWOD) are emphasized here for driving dielectric liquids, liquid crystal molecules, and conductive liquids, respectively. DEP deforms the liquid lenses when the permittivities are different between the liquid and the medium. Electrostatic force orients the liquid crystal molecules to follow the applied electric field. Electrowetting-driven liquid lenses change their focal lengths by altering the contact angle. Here we show the designs and the structures of liquid lenses to describe their mechanisms, performances and feasibilities. It is worth mentioning that the liquid lenses using electrowetting have been commercialized. No moving parts would be the most important reason to use electrical manipulations rather than mechanical ones.

Keywords

Liquid lens, electrowetting, electrowetting-on-dielectric, EWOD

1. Introduction

Liquid lenses with adjustable focal lengths have been demonstrated by the controllable liquid–liquid interface between two immiscible liquids with different refractive indices. The counterparts of the liquid lenses are the solid ones made of glass

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and crystals, which were developed more than two thousand years ago. Solid lenses are widely used in magnifying glasses, microscopes, telescopes, and cameras, extending our vision to the cells or bacteria on the microscale and heavenly bodies in the outer space. With the development of consumer devices, lenses are not only found in handheld cameras, tiny lenses are mounted inside cell phones and laptops. However, the shrunk size with necessary moving parts would limit the performance, complicate the process, and shorten the lifetime of the solid lenses. On the contrary, liquid lenses are highly adaptive and scalable. As the size of a liquid lens shrinks, the surface tension forces dominate the shape and the behavior of the liquid rather than gravity. The nature of a static water droplet has been regarded as a simple form of a convex liquid lens refracting light and enlarging images [1]. The volume of the static liquid determines its curvature and hence the focal length of the liquid lens. The microdevices integrated with a small amount of liquid offer the advantages of using inexpensive materials, being wear-proof, and exhibiting tunable focal lengths. The focal length can be further tuned through diverse technologies, classified here as mechanical and electrical means. The materials of the liquid lenses and their surroundings, the device structures, and the methods of controlling the shape of the liquids all influence the performance and quality of the liquid lenses. Here we review the liquid lenses achieved by various technologies including mechanical and electrical manipulations. In addition, we emphasize the electrical manipulations because these lenses require no moving parts, resulting in quiet operation and vibration insensitivity. Although mechanical and electrical manipulations are discussed, liquid lenses are not limited to be driven by only these two methods. Diverse mechanisms including thermo-sensitive hydrogel [2, 3], liquid crystal, electrochemistry [4], pinned-contact oscillation [5], and light controllable liquid lenses [6], have also been reported.

2. Mechanical Manipulation

On the microscale, the volume of the liquid and the design of liquid container determine the shape of the liquid lens and also the pressure inside the liquid. Moreover, the materials and the shape of the device define the optical properties of the lens. Therefore, a tunable lens would be constructed based on controllable shape of liquid, shape of the container, and material property of the liquid. These three parameters can be manipulated through electrical or mechanical manipulations. Mechanical manipulations of the liquid lens are quite straightforward to control the volume of the liquid and hence the shape of the lens. There are several methods to tune the focal length by manipulating the amount of liquid, tuning the shape of the liquid container, or changing the aperture of the liquid lens. However, the similarities between these technologies are the needs for moving parts and elastic membranes. Moving parts can be used to pump liquid, deform container, and shrink or expand the aperture. Figure 1 shows the conventional structure of a tunable microdoublet lens array [7]. The body of the device is a cavity with a flexible

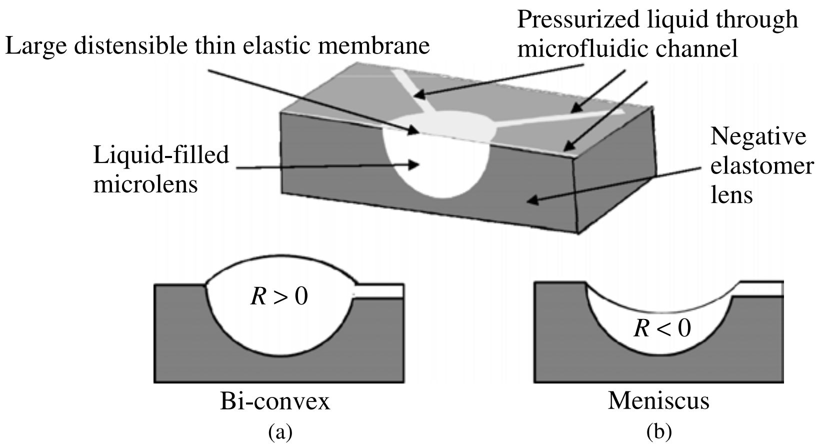


Figure 1. A tunable microdoublet lens consisting of an elastic membrane, a liquid-filled microlens cavity and a solid negative lens. (a) Bi-convex liquid lens ($R > 0$) when pumping liquid into the cavity. (b) Meniscus ($R < 0$) when pumping liquid out the cavity [7].

membrane and several microchannels to control the volume of the liquid filling the whole cavity as also shown in Fig. 1. The cavity and the membrane were made of poly(dimethylsiloxane) (PDMS, Dow Corning) through the micromolding process. With the pressure varied between positive and negative values, liquid was pumped in or out, and the membrane deformed as a biconvex lens or a meniscus as shown in Fig. 1. The architecture of the cavity defined the optic power of the lens. On the one hand, the PDMS (refractive index n_{PDMS} is 1.41) structure first defined the fixed curvature of the cavity for light refraction. On the other hand, the filling medium providing a different refractive index from that of air or PDMS further regulated the light. For example, oil (n_{oil} is 1.52) or water (n_{water} is 1.33) could be pumped into the cavity as the filling medium [7]. The refractive indices of the materials changed the focal lengths of the lens array. The pumping pressure deformed the elastomeric membrane through the filling liquid and tuned the curvature of the membrane. Liquid leakage at the membrane-cavity interface was not mentioned in the work. A similar work also demonstrated a fluidic lens with tunable focal length by manipulating the liquid volume with an external pump [8]. Figure 2 shows their concept without packaging. Simulated tunable focal lengths and experimental optical images of a US Air Force (USAF) resolution target were reported [8]. A mechanical liquid lens operated by a piezostack actuator was proposed in 2004 [9]. A fixed volume liquid container with two elastomeric membranes was driven by a piezostack actuator as shown in Fig. 3. A transparent liquid with a specific refractive index was filled and packaged in the container. The actuator pulled or pushed one of the lateral membranes to decrease or increase hydraulic pressure and forced the other membrane to deform as a concave or convex lens. The piezostack actuator is considered as an electrical component with mechanical movements for driving purposes. Moreover, Ren and Wu proposed a variable focus lens by vary-

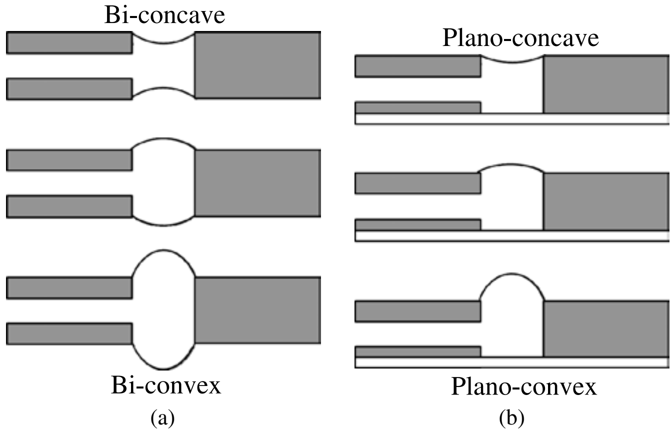


Figure 2. Scheme of the tunable liquid lens by pumping the liquid in or out of the microchannel. (a) Tunable bi-concave or bi-convex liquid lens. (b) Tunable plano-concave or plano-convex lens [8].

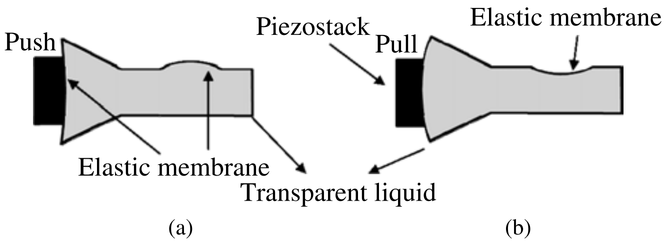


Figure 3. Scheme of the piezostack-actuated liquid lens. (a) The piezostack increases the hydraulic pressure and forces the elastic membrane to form a convex lens. (b) Otherwise, the opposite operation forms the concave lens [9].

ing the aperture and the curvature of the membrane at the same time [10]. Figure 4 shows that a liquid with fixed volume was encapsulated in the iris-like liquid lens cell composed of an elastic membrane, a glass substrate, impellers, circular periphery seal, and an actuator lever. The actuator lever controlled the lens aperture and also the curvature of the elastic membrane. Hence the lens functioned with a tunable focal length with a variable aperture.

The volume of the liquid and/or the shape of the cavity of the above-mentioned liquid lens are controlled by mechanical manipulations. The needs for external pumps or forces and elastic membranes may limit their application because of the device fatigue and the lower yield in mass manufacturing.

3. Electrical Manipulation

In recent years, liquids on the microscale have been driven by different mechanisms (e.g., external pumps and syringes, acoustic force, and electrostatic force) in microfluidic systems and have found applications in various fields (e.g., lab-on-a-chip, micro total analysis systems (μ-TAS), and liquid lenses) [11–15]. The manipulation

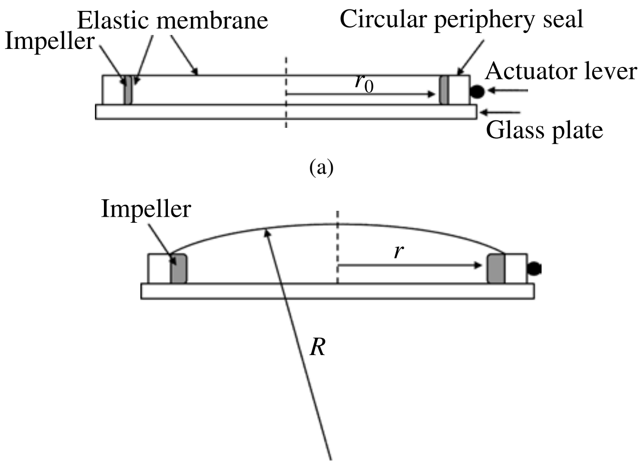


Figure 4. Scheme of the liquid lens cell with (a) no focus effect with an aperture radius r_0, (b) focusing effect with an aperture radius $r < r_0$ and a curvature of R [10].

of a small amount of liquid is essential for the applications of microfluidic systems, especially to commercial products, including liquid lenses. Although mechanical manipulations by external pumps are straightforward, the whole system would be difficult to shrink for integration into a compact consumer device. The moving parts of solid and liquid lenses driven mechanically cause deterioration and noise during operation and encounter challenges in mass production. For example, a traditional camera is usually composed of several solid lenses in the light path. By using liquid lenses, one or more solid lenses would be replaced to control the focal length. Additionally, electrical microfluidic manipulations can be regarded as internal pumps driving liquid lens with no moving parts. The electrically driven liquid lenses with limited and precise volumes are more suitable for the mass production and device packaging. Without mechanical components, the electrically driven liquid lenses are quiet and durable, while the high optical quality is maintained. The numerous materials applicable to liquid lenses provide a wide range of operational temperature.

Here we classify the electrically driven liquids into two groups, conductive and insulating liquids. Two major electric forces, electrowetting-on-dielectric (EWOD) [16–19] and dielectrophoresis (DEP) [20–22], to manipulate various liquids in microfluidic systems are emphasized here. A liquid crystal is categorized into a special dielectric liquid having unique optical properties. Liquid crystals, conductive liquids, and insulating liquids were successfully driven by electrostatic forces, EWOD, and DEP, respectively. In addition to liquid movement, with proper design of the device structure and appropriate combination of the conductive and insulating liquids, EWOD or DEP would alter the shape of the liquid droplet to achieve tunable focal lengths.

4. Electrical Manipulation — Insulating Liquids and Liquid Crystals

DEP has been studied for manipulating polarizable particles and liquids with an electric field gradient [20, 23]. The force exerted on driven particles is proportional to the gradient of the square of the electric field [20]. In addition, the proper dimension of the device or the liquid channel is essential to DEP. Liquids with higher permittivities would be drawn into the strong electric field region originally filled with the surrounding medium with a lower permittivity. The DEP force to drive liquids by applying voltage between a pair of parallel electrode plates spaced d apart can be described as [14, 20]:

$$\mathrm{F_{DEP}} = \frac{\varepsilon_0(\varepsilon_\mathrm{L} - \varepsilon_\mathrm{M})W}{2d}V^2, \tag{1}$$

where ε_0 is the permittivity of vacuum, 8.85×10^{-12} F/m, and ε_L and ε_M are the relative permittivities of the driven liquid and the surrounding medium, respectively. W is the width of the electrode. Again, it can be seen from the equation that DEP drives the liquid with a higher permittivity by a non-uniform electric field. Figure 5 shows a dielectrically actuated liquid lens reported by Cheng and Yeh [24]. The cavity contained two immiscible liquids with different permittivities and refractive indices. In that work, the difference in the relative permittivities was about 35, and the refractive indices of the high permittivity liquid and the low permittivity liquid were 1.4 and 1.6, respectively. The density of the liquids was almost the same to minimize the gravitational effect. The shape of the droplet was deformed by the non-uniform electric field provided by two concentric electrodes to attract the liquid with a higher permittivity rather than the surrounding medium with a lower permittivity. The focal length tuning was demonstrated by tunable electric fields where the DEP force was effective at the interface of the two immiscible liquids and contracted the droplet to decrease the effective curvature [25]. The droplet was driven from 0 V to 200 V and the focal length changed from 34 mm to 12 mm. Sim-

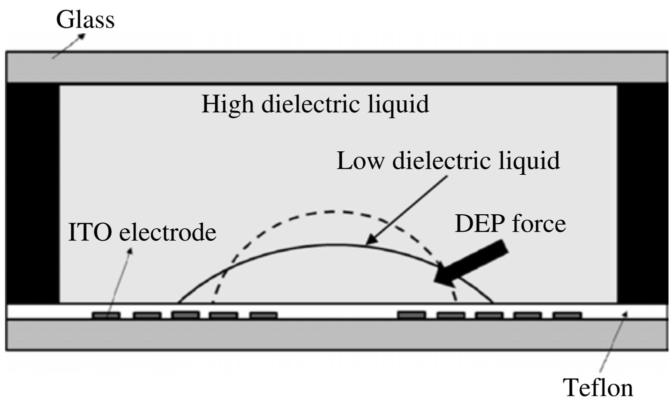


Figure 5. Illustration of a dielectric liquid lens. The droplet in electric field is contracted to a new state with smaller effective curvature (dashed line) by DEP force [24].

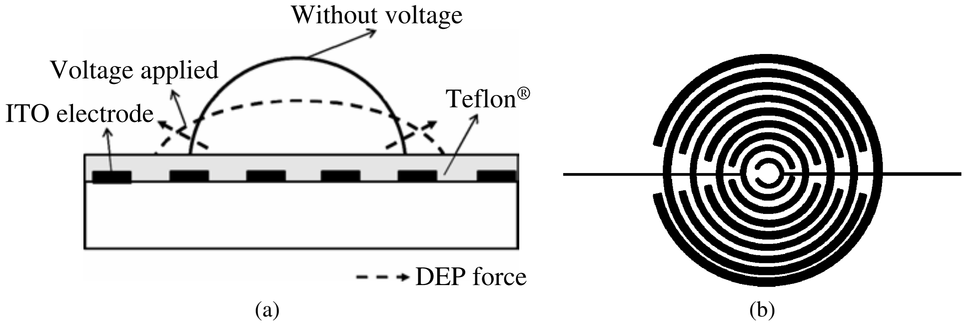


Figure 6. (a) Scheme of a deformable liquid crystal droplet lens driven by DEP. (b) Top view of the concentric ITO electrode in (a) (not to scale) [25].

ilar structure and theory can be applied to liquid crystal materials driven by electric fields. Figure 6 shows a concentric indium-tin-oxide (ITO) electrode contributing a non-uniform electric field to drive a liquid crystal droplet lens. The effective focal length is tuned by the applied electric field [25]. The liquid lens formed by a small droplet resulted in the focal length change at the small scale, thus the effective optical power was quite high.

Liquid crystal (LC) molecules' promising electro-optic properties have been proven nowadays in liquid crystal displays (LCDs) with continuously improving qualities. The LC molecules are usually composed of several different molecules to have a suitable electro-optic property. With the nature of birefringence and anisotropy of refractive index, LC was also applied to liquid lens studies. In the nematic phase, the molecular axis with high dielectric constant tends to be parallel to the external electric field. Due to the different refractive indices in the different axes of the LC molecule, direction-dependent refractive indices of LC molecules are quite essential to the LC lenses. The effective refractive index, n, of the LC molecules can be the index in a stable state when there is no external voltage applied. When an external voltage is applied, the LC molecules' axes with higher dielectric constant turn to be parallel to the electric field and the refractive index changes to the index of the axis with lower dielectric constant. The tunable refractive index of the LC lens makes its focal length adjustable. The LC lens is one of the emerging techniques suitable for 3D glasses and optical tweezers [26–28]. LC molecules can be further dispersed in a matrix of small molecules or polymer for different conformations and applications [29–33]. Moreover, the structure of the device and the directions of the alignment layers are also essential to the functions of the LC liquid lenses.

With the design of the liquid container similar to that mentioned in the mechanical manipulation section, the LC molecules can be filled in as an optic liquid. Figure 7 shows a photo-definable container fabricated by a molding process [34]. The LC molecules were sandwiched between the container and an ITO glass with an alignment layer. When no voltage was applied, the curvatures of the polymer-based cavity and the LC molecules presented the initial focusing property. When

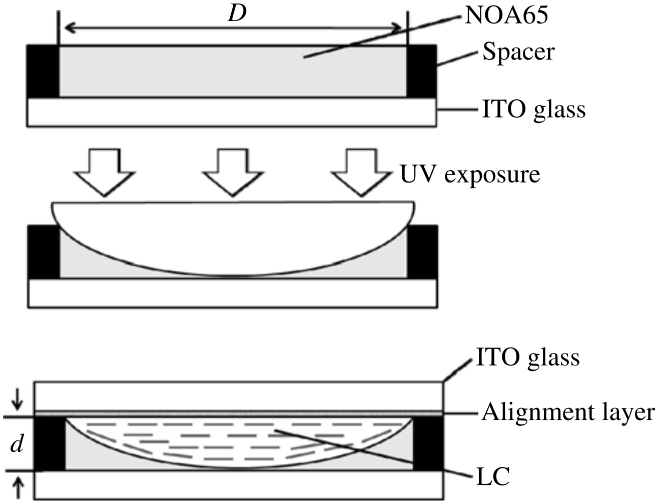


Figure 7. Fabrication process of a polymer–LC lens with tunable focal length. The diameter of spherical lens *D*, and the center thickness of lens *d* define the curvature and the shape of the cavity [34]. Norland optical adhesive 65 (NOA65) is a clear, colorless UV-cured adhesive.

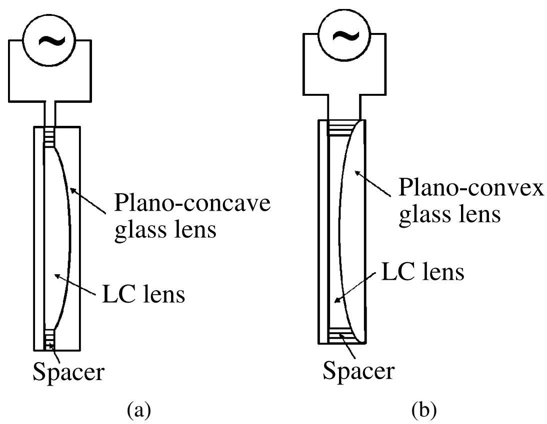


Figure 8. Schemes of the LC-glass lens cells (a) plano-convex LC lens with plano-concave glass lens, (b) plano-concave LC lens with plano-convex glass lens [35].

the external voltage was applied, the refractive index of the LC molecules matched the index of polymer cavity and resulted in a homogeneous device with no focusing effect [34]. Plano-convex and plano-concave LC lenses have been demonstrated in earlier works as shown in Fig. 8 [35]. The temperature dependence and the voltage-controlled focal lengths of LC lenses have also been reported. The LC molecules can be filled in a cavity with curved or the flat substrates [36]. Different designs, including the shapes of cavity, directions of the alignment layers and the polarizer layers, materials of the LC and the cavity, types of the LC, and the dimensions of the device, all result in different performances and applications. Furthermore, the

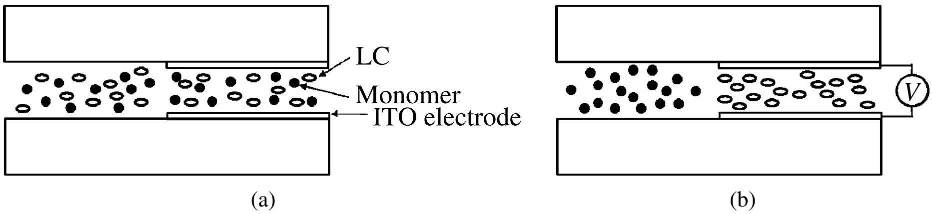


Figure 9. Mechanism of an LC concentration redistribution lens: (a) No voltage. (b) When the voltage is applied, the LC molecules are attracted by electric field and monomers difuse into low electric field region [29].

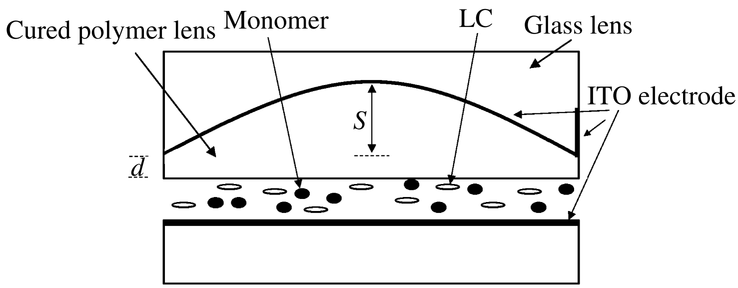


Figure 10. Scheme of the device structure of a flat spherical lens cell. Glass lens and cured polymer lens form top plate with curved ITO electrode which drives LC molecules by non-uniform electric field [29].

mixed solution containing LC molecules and additives provides various characteristics. As can be seen in Fig. 9, electrically actuated molecular redistribution has been demonstrated by using mixtures of LC molecules and monomers [29]. The type of LC molecules can have positive ($\Delta\varepsilon > 0$) or negative ($\Delta\varepsilon < 0$) dielectric isotropy which influences the function of the LC lens, initial state, and field-induced reorientation state [37]. In this study, the dielectric constant of LC molecules was higher than the dielectric constant of the monomers, thus the LC molecules would be attracted towards external electric field rather than the monomers [29]. Moreover, the DEP force on the LC molecules depends on the LC polarizability and the gradient of electric field strength. With a pre-coated alignment layer on the electrode, the LC molecules would follow the rubbing direction and thus would result in the focusing effect in the uniform electric field. The same effect can be found with a non-uniform electric field as shown in Fig. 10, where one of the electrodes was coated onto a plano-concave lens, and the other electrode was coated onto a flat glass substrate. Due to the motion and diffusion of the LC molecules, this type of adaptive LC lens showed a slower response than other LC lenses without the motion of LC molecules. LC molecules can be further doped into a polymer matrix as polymer dispersed liquid crystal (PDLC) after curing [30–33]. Bendable polymer matrix provides flexibility and constrains the motion of the LC molecules. Figure 11 shows the top-view of a liquid lens on the hydrophobic PDLC layer [38]. The lens was driven *via* EWOD as shown in Fig. 12(a) and (b). The surface wetta-

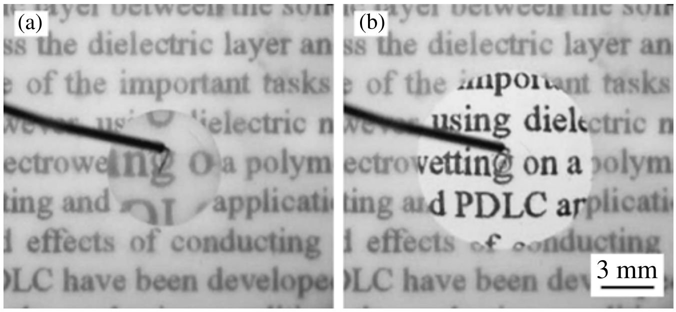


Figure 11. An electrowetting-driven liquid lens on PDLC that is regarded as the dielectric layer with tunable transmittance. The image under the liquid lens could be magnified or minified with the tunable focal length. (a) No voltage applied. (b) Voltage applied [38].

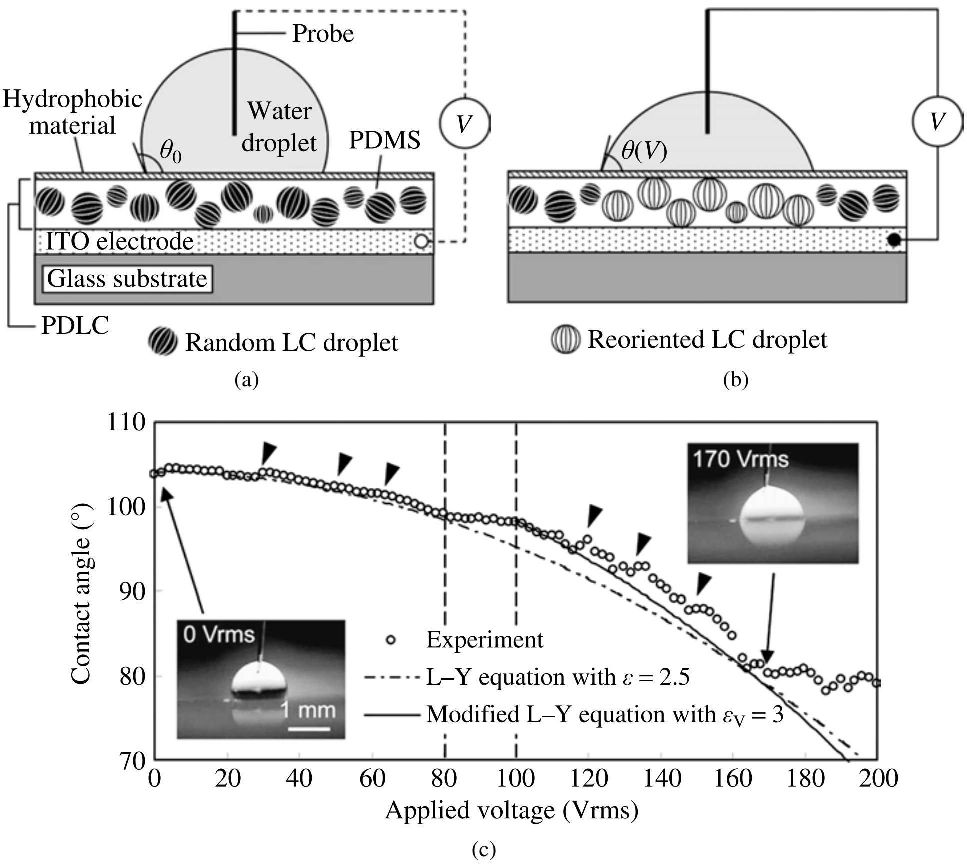


Figure 12. Electrowetting of a sessile droplet on PDLC. (a) No voltage applied. (b) Voltage applied. (c) Measured contact angles (circles) plotted against the applied voltage with two theoretical curves [38].

bility and the transmittance of the PDLC layer were controlled during driving. The image under the liquid lens could be magnified or minified with the tunable focal length.

5. Electrical Manipulation — Conductive Liquid

A conductive liquid can be driven by electrowetting and EWOD [16–19]. Electrowetting at the interface between liquid metal and conductive electrolyte was first studied in 1875 [39]. The phenomenon could be explained from the viewpoint of the electrical double layer at the interface. The addition of a dielectric layer (i.e., EWOD) provides protection of the electrodes and hence increases the reversibility of electrowetting. Besides, the applied AC voltage with low frequencies drops across the dielectric layer and changes the contact angle of a liquid droplet placed on the originally hydrophobic dielectric layer surface rather than forming a non-uniform electric field in the droplet at high frequencies [40]. Thus, EWOD is an electric driving mechanism which alters the contact angle and shape of the conductive liquid, serving as a powerful tool to manipulate a conductive liquid on the microscale. The liquid cohesion force and the electrically tunable surface tension dominate on the microscale and effectively drive the droplet to form a convex lens or re-arrange the distribution of the dye-covered area to achieve displays [41–44]. For EWOD-driven liquid lenses, the external voltage applied across the hydrophobic dielectric layer decreases the contact angle and changes the shape and the curvature of the conductive liquid following the Lippmann–Young (L–Y) equation that describes the relationship between the contact angle, surface tension, and voltage:

$$\cos\theta_{\mathrm{V}} = \cos\theta_0 + \frac{\varepsilon_0\varepsilon}{2\gamma t}V^2, \tag{2}$$

where V is the applied voltage across the dielectric layer, θ_0 and θ_{V} are the contact angles before and after applied voltage, respectively, ε_0 is the permittivity of vacuum, ε and t are the relative permittivity and the thickness of the dielectric layer, respectively, and γ is the surface tension between the liquid and surrounding medium. From the Lippmann–Young equation, the contact angle can be tuned through the external voltage. AC electric signals are usually used to avoid the polarity dependence of the applied voltage and reduce the charging effect [45].

The hydrophobic layer and device structure determine the initial contact angle θ_0 and the initial focal length of the liquid lens. The thickness t and the relative permittivity ε of the dielectric layer are related to the performance of the liquid lens and the contact angle–voltage (θ–V) curve as shown in Fig. 12(c), measured from an EWOD-driven sessile droplet that would perform as a liquid lens. The electrical, thermal, mechanical and optical properties of dielectric materials all influence the $\theta - V$ curve and the lens performance. Numerous dielectric materials, for example, SiO_2, Si_3N_4, poly(dimethylsiloxane) (PDMS), poly(p-xylylene) (parylene) [46], poly(tetrafluoroethylene) (PTFE) [47], CYTOP (amorphous perfluoropolymer from Asahi Glass Ltd.) [48], and polymer dispersed liquid crystals (PDLCs) [38], have been investigated in EWOD devices for their insulating, superhydrophobic or optical properties. As mentioned in the last section, Fig. 11 demonstrates EWOD on PDLC to exhibit a liquid lens with tunable focal length as well as simultaneous transmittance variations [38]. In addition to the PDLC case, for the liquid lens applications, the dielectric layer should be highly transparent, thin, and of high relative permittivity to lower the operating voltage. Furthermore, the combination of conductive liquid and the surrounding medium determines the interfacial tension γ and the differences in refractive index and density of the liquid lens. All these parameters are material-dependent. The refractive index relates to the nature and optical power of the lens. The density is critical to stabilize the immiscible liquids and to minimize gravitational effect. To achieve a stable liquid lens, it is important to consider the gravitational effect. Thus, the densities of the liquids need to be almost the same. Varioptic (France) designed a concentric structure to confine the droplet in the center as shown in Fig. 13 [49]. A series of papers have fully discussed and studied several fundamental issues referred to EWOD-driven liquid lenses, including the gravitational effect, structure and design, materials, thermodynamic effect, tilting effect and compensation, power consumption, response time, physical limitations, and auto-focusing functions [49–59]. The concentric EWOD electrodes design shown in Figs 13 and 14 was to stabilize the droplet in the optical axis by the side electrodes [57]. Figure 15(a) shows a real product, Arctic 416, from Varioptic. The diameter of the packaged EWOD liquid lens is 7.75 mm. The applications are 2D barcode readers, industrial cameras, dental cameras, and biometrics. Figure 15(b) shows an industrial barcode reader from Cognex (USA), with a packaged Arctic 416 module.

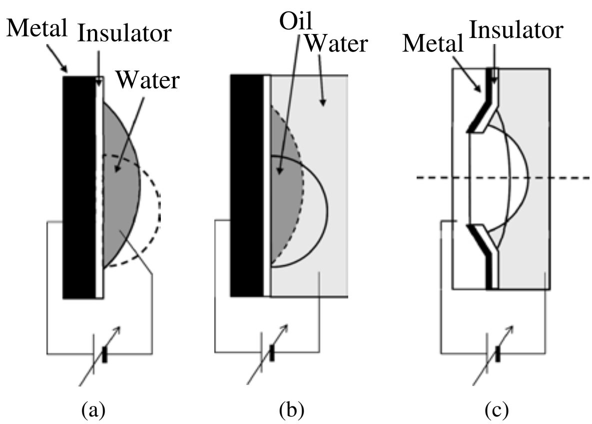


Figure 13. Scheme of the device design to stabilize droplet in the optical axis where the droplet is confined by the concentric side electrodes. (a) Usual electrowetting phenomenon changes droplet shape by applied voltage. (b) Using two immiscible liquids of the same density suppresses optical distorsion caused by gravity. (c) Concentric electrodes provide a stable optical axis and avoid optical pertubation at the liquid–liquid interface [49].

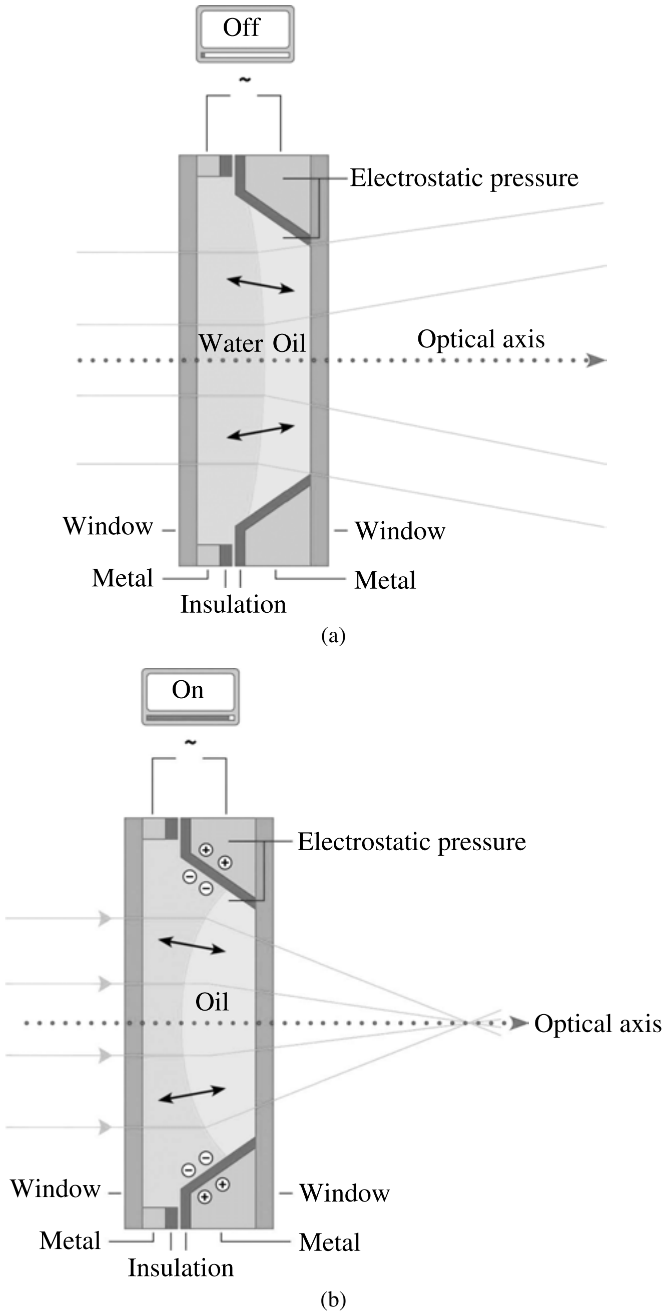
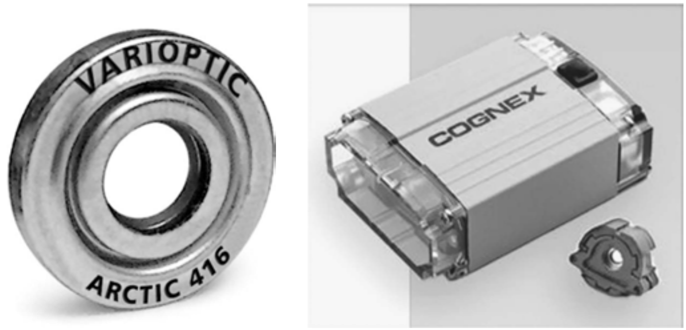


Figure 14. Scheme of the device during operation. (a) Water medium and oil droplet form plano-convex lens and plano-concave lens, respectively. As, the refractive index of oil is higher than that of water, the device diffuses the light when no voltage is applied. (b) When the voltage is applied, the contact angle of the water medium is decreased to form a plano-concave lens, and the oil droplet is contracted to a plano-convex lens. The device focuses the light passing through it [57].



(a) (b)

Figure 15. Photos of real products. (a) Arctic 416 liquid lens from Varioptic. The miniaturized electrowetting liquid lens is packaged in a diameter of 7.75 mm. Its proven performance has made it a choice for demanding applications such as 2D barcode readers, industrial cameras, dental cameras, and biometrics. (b) An industrial barcode reader from Cognex, with a packaged Arctic 416 module.

A liquid droplet with a high refractive index can be regarded as a convex lens without voltage application. It becomes a concave lens when the side electrodes are energized. By EWOD, liquid lenses with high optical power and fast response were achieved.

6. Conclusion

We reviewed liquid lenses and the driving mechanisms were classified into mechanical and electrical ones. In the mechanical manipulations, external pump, elastic membrane and various actuators are needed and are used to control the hydraulic pressure, volume of liquid, and the shape of liquid lenses, which results in tunable focal lengths. Mechanical manipulations can drive most of the liquids regardless of their electrical properties such as conductivity and permittivity, while the liquids' electrical properties need to be carefully considered when using electrical manipulations. However, liquid lenses driven electrically are more suitable when scaling down because no moving parts are necessary. In addition, they are quiet, easily produced, inexpensive, and durable in a wide temperature range. Different electrical manipulations, including DEP, EWOD, and electrostatic forces, were described. The diverse driving mechanisms expand the field of liquid lenses and their applications, including camera and other consumer products as well as lab-on-a-chip (LOC) and optofluidic applications.

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References

1. H. H. Myint, A. M. Marpaung, H. Kurniawan, H. Hattori and K. Kagawa, *Phys. Educ.* **36**, 97 (2001).
2. L. Dong, A. K. Agarwal, D. J. Beebe and H. Jiang, *Nature* **442**, 551 (2006).
3. H. Yang, Y.-H. Han, X.-W. Zhao, K. Nagai and Z.-Z. Gu, *Appl. Phys. Lett.* **89**, 111121 (2006).
4. C. A. López, C.-C. Lee and A. H. Hirsa, *Appl. Phys. Lett.* **87**, 134102 (2005).
5. C. A. López and A. H. Hirsa, *Nature Photonics* **2**, 610 (2008).
6. B. A. Bezuglyĭ, S. V. Shepelenok and N. A. Ivanova, *Tech. Phys. Lett.* **24**, 973 (1998).
7. K.-H. Jeong, G. L. Liu, N. Chronis and L. P. Lee, *Opt. Express* **12**, 2494 (2004).
8. P. M. Moran, S. Dharmatilleke, A. H. Khaw, K. W. Tan, M. L. Chan and I. Rodriguez, *Appl. Phys. Lett.* **88**, 041120 (2006).
9. H. Oku, K. Hashimoto and M. Ishikawa, *Opt. Express* **12**, 2138 (2004).
10. H. Ren and S.-T. Wu, *Appl. Phys. Lett.* **86**, 211107 (2005).
11. T. M. Squires and S. R. Quake, *Rev. Mod. Phys.* **77**, 977 (2005).
12. G. M. Whitesides, *Nature* **442**, 368 (2006).
13. H. Craighead, *Nature* **442**, 387 (2006).
14. S.-K. Fan, W.-J. Chen, T.-H. Lin, T.-T. Wang and Y.-C. Lin, *Lab Chip* **9**, 1590 (2009).
15. S. K. Y. Tang, C. A. Stan and G. M. Whitesides, *Lab Chip* **8**, 395 (2008).
16. S. K. Cho, H. Moon and C.-J. Kim, *J. Microelectromech. Syst.* **12**, 70 (2003).
17. U.-C. Yi and C.-J. Kim, *J. Micromech. Microeng.* **16**, 2053 (2006).
18. S.-K. Fan, H. Yang and W. Hsu, *Lab Chip* **11**, 343 (2011).
19. J. Gong and C.-J. Kim, *Lab Chip* **8**, 898 (2008).
20. H. A. Pohl, *Dielectrophoresis*. Cambridge University Press, New York (1978).
21. J. A. Schwartz, J. V. Vykoukal and P. R. C. Gascoyne, *Lab Chip* **4**, 11 (2004).
22. O. D. Velev, B. G. Prevo and K. H. Bhatt, *Nature* **426**, 515 (2003).
23. H. Morgan and N. G. Green, *AC Electrokinetics: Colloids and Nanoparticles*. Research Studies Press, Baldock, UK (2003).
24. C.-C. Cheng and J. A. Yeh, *Opt. Express* **15**, 7140 (2007).
25. C.-C. Cheng, C. A. Chang and J. A. Yeh, *Opt. Express* **14**, 4101 (2006).
26. T. Nose and S. Sato, *Liq. Cryst.* **5**, 1425 (1989).
27. T. Nose, S. Masuda and S. Sato, *Jpn. J. Appl. Phys.* **31**, 1643 (1992).
28. M. Honma, T. Nose and S. Sato, *Jpn. J. Appl. Phys.* **38**, 89 (1999).
29. H. Ren, Y.-H. Lin and S.-T. Wu, *Appl. Phys. Lett.* **88**, 191116 (2006).
30. J. L. Fergason, *SID Int. Symp. Digest Tech. Papers* **16**, 68 (1985).
31. J. W. Doane, N. A. Vaz, B.-G. Wu and S. Žumer, *Appl. Phys. Lett.* **48**, 269 (1986).
32. P. S. Drzaic, *Liquid Crystal Dispersions*. World Scientific, Singapore (1995).
33. H. Ren, Y.-H. Fan, Y.-H. Lin and S.-T. Wu, *Opt. Commun.* **247**, 101 (2005).
34. Y. J. Liu, X. W. Sun and Q. Wang, *J. Cryst. Growth* **288**, 192 (2006).
35. S. Sato, *Jpn. J. Appl. Phys.* **18**, 1679 (1979).
36. H. Ren, Y.-H. Fan, S. Gauza and S.-T. Wu, *Appl. Phys. Lett.* **84**, 4789 (2004).
37. C.-C. Cheng, C. A. Chang C.-H. Liu and J. A. Yeh, *J. Opt.* **8**, S365 (2006).
38. S.-K. Fan, C.-P. Chiu and J.-W. Lin, *Appl. Phys. Lett.* **94**, 164109 (2009).
39. G. Lippmann, *Annals Chim. Phys.* **5**, 494 (1875).
40. S.-K. Fan, P.-W. Huang, T.-T. Wang and Y.-H. Peng, *Lab Chip* **8**, 1325 (2008).
41. F. Gindele, F. Gaul and T. Kolling, *Proc. SPIE* **5455**, 89 (2004).
42. R. A. Hayes and B. J. Feenstra, *Nature* **425**, 383 (2003).

43. Z. Wan, H. Zeng and A. Feinerman, *Appl. Phys. Lett.* **89**, 201107 (2006).
44. N. R. Smith, D. C. Abeysinghe, J. W. Haus and J. Heikenfeld, *Opt. Express* **14**, 6557 (2006).
45. S.-K. Fan, H. Yang, T.-T. Wang and W. Hsu, *Lab Chip* **7**, 1330 (2007).
46. M. Dhindsa, S. Kuiper and J. Heikenfeld, *Thin Solid Films* **519**, 3346 (2011).
47. W. J. J. Welters and L. G. J. Fokkink, *Langmuir* **14**, 1535 (1998).
48. S. Berry, J. Kedzierski and B. Abedian, *Langmuir* **23**, 12429 (2007).
49. L. Saurei, J. Peseux, F. Laune and B. Berge, in: *Proceedings of the 10th MicroOptics Conference*, p. 1 (2004).
50. R. Day, E. Lacot, F. Stoeckel and B. Berge, *Appl. Opt.* **40**, 1921 (2001).
51. C. Gabay, B. Berge, G. Dovillaire and S. Bucourt, *Proc. SPIE* **4767**, 159 (2002).
52. J. Crassous, C. Gabay, G. Liogier and B. Berge, *Proc. SPIE* **5639**, 143 (2004).
53. L. Saurei, G. Mathieu and B. Berge, *Proc. SPIE* **5249**, 288 (2004).
54. E. Simon, P. Craen, H. Gaton, O. Jacques-Sermet, F. Laune, J. Legrand, M. Maillard, N. Tallaron, N. Verplanck and B. Berge, *Proc. SPIE* **7716**, 77160I-1 (2010).
55. B. Berge, *Kogaku Shinpojiumu Koen Yokoshu* **31**, 55 (2006).
56. B. Berge, in: *Proceedings of the 18th IEEE International Conference on Micro Electro Mechanical Systems (MEMS 2005)*, Miami, Florida, USA, p. 227 (2005).
57. B. Berge, *Nikkei Electronics* **911**, 129 (2005).
58. B. Berge and J. Peseux, *Eur. Phys. J. E* **3**, 159 (2000).
59. R. Shamai, D. Andelman, B. Berge and R. Hayes, *Soft Matter* **4**, 38 (2008).