Design and wavefront characterization of an electrically tunable aspherical optofluidic lens

KARTIKEYA MISHRA, ADITYA NARAYANAN, AND FRIEDER MUGELE*

Physics of Complex Fluids, Department of Science and Technology, MESA + Institute, University of Twente, P. O. Box 217, 7500 AE, Enschede, The Netherlands

*f.mugele@utwente.nl

Abstract: We present a novel design of an exclusively electrically controlled adaptive optofluidic lens that allows for manipulating both focal length and asphericity. The device is totally encapsulated and contains an aqueous lens with a clear aperture of 2mm immersed in ambient oil. The design is based on the combination of an electrowetting-driven pressure regulation to control the average curvature of the lens and a Maxwell stress-based correction of the local curvature to control spherical aberration. The performance of the lens is evaluated by a dedicated setup for the characterization of optical wavefronts using a Shack Hartmann Wavefront Sensor. The focal length of the device can be varied between 10 and 27mm. At the same time, the Zernike coefficient $Z_4^0$, characterising spherical aberration, can be tuned reversibly between 0.059 waves and 0.003 waves at a wavelength of $\lambda = 532\text{nm}$. Several possible extensions and applications of the device are discussed.

© 2019 Optical Society of America under the terms of the OSA Open Access Publishing Agreement

1. Introduction

For a long time, the development of lenses with variable focal length has been a central focus of adaptive microoptics [1–3]. Various approaches have been demonstrated, including deformable polymeric lenses, liquid lenses with free surfaces and liquid lenses covered by an elastomeric membrane. Most of the proposed approaches aimed at spherical lenses of variable curvature. In particular in optofluidics, various actuation mechanisms were explored to tune liquid lenses, including variations of the pressure or the volume of the lens fluid and the wettability of the substrate. Some approaches even involved dynamic excitation of the fluid in combination with synchronized image acquisition using high speed cameras to achieve ultrafast actuation [4]. Electrowetting (EW) proved to be a particularly versatile approach in this respect because it allows for very fast actuation and a wide range allowing to achieve both positive and negative focal lengths with the same device, simply by applying more or less voltage [5–7]. If operated with density matched ambient liquid media, such lenses proved to be very reliable, fast, and resistant against mechanical vibrations.

A key problem in microoptics is often the presence of strong aberrations, in particular if the full aperture of a lens is used to collect a sufficient amount of light. Because of constrained space, microoptical systems often don’t allow for standard combinations of lenses to compensate for aberrations. This typically leads to rather poor image quality. To respond to this challenge, several approaches have been proposed in recent years in order to generate non-spherical microlenses with tunable shape to compensate for various forms of geometric aberrations. In case of elastomeric lenses, mechanical actuators were used to distort surface profiles and suppress or deliberately induce astigmatism [8]. In case of membrane-covered liquid lenses, membranes with custom-engineered thickness profiles were used to achieve lenses of minimum spherical aberration within certain ranges of focal length [9]. More recently, sophisticated tubular lenses actuated by EW with segmented electrodes on the inside of the tube were demonstrated to efficiently compensate astigmatism [10]. Numerical simulations using a genetic algorithm indicate that this approach allows for very efficient improvements of the point spread function and Strehl ratio of an imaging system [10,11].
However, using this approach it will always be difficult to compensate for spherical aberration because any free liquid surface, no matter how complex the boundary condition, is always a surface of constant mean curvature by the laws of capillarity, unless additional external forces are applied. This is in contrast to the fundamental origin of spherical aberration, which arises from the fact that perfect imaging can only be obtained if the curvature of the refracting surface is not constant but decreases with increasing distance from the optical axis. A convincing solution to overcome this problem was first demonstrated by Zhan et al. [12]. These authors demonstrated that electric fields could be used to distort liquid surfaces in a manner that approaches an ideal aspherical lens shape. This was achieved by placing a homogeneous flat electrode at a fixed voltage above electrically insulated drops of photo-curable polymers. This lead to aspherical microlenses that were subsequently crosslinked in their deformed state under voltage. As a consequence of solidification, the drops obviously lost their tunability. Moreover, the suffered from surface roughness.

A few years later, inspired by EW-experiments on the Cassie-to-Wenzel transition on superhydrophobic surfaces [13] and numerical calculations of the equilibrium liquid surface profiles in electric fields [14], Mishra et al. [15] implemented a liquid lens design that allowed for reversible tuning of both longitudinal spherical aberration (LSA) and focal length over a substantial range. While the equilibrium shape of the lens is determined by the local balance of Laplace pressure and electrical Maxwell stress as in the approach of [12], the possibility of simultaneous independent variation of the hydrostatic pressure difference between the aqueous lens fluid and an ambient oil in combination with the asphericity-controlling voltage enabled independent variation of LSA and focal length. This allowed for instance, to vary the focal length from 2 to 20mm while keeping the LSA – as inferred from side view images of the lens – at zero. In subsequent extensions of the approach, the flat electrode used to suppress spherical aberration was replaced in numerical simulations first by a stripe-shaped electrode to induce controlled astigmatism [16] and eventually by an array of individually addressable electrodes [17]. Ray-tracing analysis of these numerically calculated surface profiles as well as experimental ones [18] and their analysis in terms of Zernike coefficients and modulation transfer function suggested that various types of geometric aberrations could indeed be controlled by this approach.

The purpose of the present contribution is twofold: First, we combine the approaches of Murade et al. [19] with an EW-controlled pressure regulation to vary the overall lens curvature and the one of Mishra et al. [15] with a Maxwell stress-controlled local variation of the local curvature to suppress spherical aberration into a single, all-encapsulated device. This lens is actuated exclusively by electrical control signals and allows for a wide tuning range of both focal length and spherical aberration. Second, we quantify experimentally the wavefront distortions generated by our device. To this end, we set up a testing platform using a Shack-Hartman wavefront sensor (SHWS) that allows us to measure wavefronts following previous reports in the literature [8,20,21].

2. Device design and operating principle

The design of the device is shown in Fig. 1. The core of the lens consists of a top plate (number (1) in Fig. 1a), aperture plate (2), and bottom plate (3), all kept apart by spacers. The top and bottom plates are 0.5mm thick glass plates with transparent ITO electrodes on the inner side of the device. The aperture plate is 0.17mm thick. All plates are 2.7×2.7 cm² wide and electrically insulated from each other. The separation between top and aperture plate is 2.5mm, the one between aperture and bottom plate is 1.5mm. This sandwich structure is sealed with O-rings and encased by outer backing plates with dimensions of 5×5 cm². The actual lens is a plano-convex lens formed by a drop of fixed volume of a saturated aqueous LiBr solution (refractive index $n_r = 1.461$; conc. = 64% by mass; density $\rho = 1700 g/cm^3$) that is sandwiched between the bottom plate and the aperture plate. The drop partially
protrudes through the central aperture (diameter 2mm) where it forms the refracting interface with the surrounding silicone oil (Sigma Aldrich; cat. Nr. 317667; $n_w = 1.40$; $\rho_{oil} = 0.913g/cm^3$) that fills the rest of the device. The interfacial tension between the oil and water is $\gamma = 0.04N/m$. The edge of the oil-water interface is pinned along the edge of the aperture. To ensure good pinning, the aperture plate is Au-coated and hydrophobized with a self-assembled monolayer by dipping into a 1% thiol solution in ethanol for 24h. On the bottom side of the middle plate, a notch with a radius of 3.5mm pins the upper contact line of the sandwiched drop. The bottom plate is functionalized for EW. It consists of a glass plate with a transparent ITO electrode that is covered by a thin (~2nm) layer of amorphous fluoropolymer (Teflon AF 1600). Upon applying a voltage between this ITO layer and the electrically grounded aperture plate, which is in direct contact with the aqueous phase, the contact angle on the bottom plate can be varied reversibly between 165° at zero voltage and 65° at a maximum voltage of $U_{max} = 120V$, as indicated by the green arrows in Fig. 1a. This decrease follows the classical Young-Lippmann equation $\cos \theta(U) = \cos \theta_0 + cU^2/2$ of electrowetting, where $\theta_0$ is Young’s angle and $c$ is the capacitance per unit area between the drop and the ITO electrode across the Teflon AF layer (see [22] for the general principles of electrowetting). The contact angle hysteresis is less than 5°. Assembly of the device is preferably performed fully under oil to avoid entrapment of air bubbles.

The physical operating principle to reduce spherical aberration is based on the electrical stresses pulling on the lens surface upon applying a high voltage $U_a$ (up to 1500V) applied between the aperture plate and the second ITO layer on the top plate. Since the drop is electrically conductive and grounded, the radially varying distance between the lens surface and the top electrode gives rise to an inhomogeneous electric field $E(r)$, which decreases with increasing distance $r$ from the optical axis, as indicated by the red dashed lines in Fig. 1a. The electric field exerts a Maxwell stress $\Pi_L(r) = \varepsilon \varepsilon_0 E(r)^2/2$ on the liquid surface, which also decreases with increasing $r$ ($\varepsilon \varepsilon_0$: dielectric permittivity of the oil). In equilibrium, Maxwell stress is balanced by the position-dependent Laplace pressure $\Delta p_L$ everywhere along the lens surface:

$$\Delta p_L(r) = \frac{\gamma \kappa(r)}{2} = \frac{\varepsilon \varepsilon_0 E(r)^2}{2} = \Pi_L(r)$$

1

Fig. 1. a) Schematic view of the device consisting of three electrodes (top (1), middle (2), bottom (3); thick solid lines); voltages $U_a$ and $U_p$ on the top and bottom plate w.r.t. the grounded middle electrode control pressure and asphericity. Dark grey: aqueous drop at zero voltage; light grey: at finite $U_a$ and $U_p$. Green arrows indicate contact line displacement due to electrowetting. Red dashed lines: schematic distribution of electric field lines controlling asphericity. Blue arrow: light path. b) photograph of the assembled device.
Here $\kappa(r)$ is the $r$-dependent curvature of the lens. Since the lens fluid is conductive, lens shape and electric field distribution adjust each other in a self-consistent manner to reach an equilibrium lens shape with a curvature that is maximum on the optical axis and decreases towards the edge of the lens [14], as required for a perfectly refracting aspherical lens profile. By varying $U_g$, the initially spherical cap-shape lens can be distorted more and more, leading to a voltage-dependent spherical aberration of the lens as first described in [15].

3. Optical setup

The optical setup consists of a measurement arm in which the optofluidic lens under test is placed and a reference arm through which the incident planar wave front from a laser source light passes directly, see Fig. 2. The incoming beam from the laser source ($\lambda = 532\text{nm}$; max. power $P = 250\text{mW}$) is expanded from 0.8mm to 8mm beam diameter using a Gaussian beam expander (BE 10M-A, 10X Magnification, BE, Thorlabs). The expanded beam is split by a non-polarizing beam splitter (BS013, 1", 400 – 700nm, 50:50 intensity split ratio, BS1) into a reference and a measurement beam.

The measurement beam is directed vertically via two mirrors (M and M') through an infinity corrected microscope objective (MO, Mitutoyo, Plan Apo 10x/NA = 0.28) and the test lens.

![Fig. 2. Schematic of the optical setup. BE: beam expander. The reference arm constitutes a laser beam passing through BS1, BS2, Relay lens system and finally falling on the CCD of Shack-Hartmann wavefront sensor (SHWS). Measurement arm consists of laser beam splitting by BS1, traversing vertically through mirrors (M) and M', passing sequentially through Microscope objective (MO), lens device, Relay lens system and finally falling on SHWS. The CCD camera (C1) is used for the interferometric alignment. Shutter is used to block the reference beam, while carrying out measurements via measurement arm.](image)

The objective is mounted on a kinematic mount (KM100R), which is attached to vertically oriented motorized linear translation stage (LTS-300, Thorlabs) with a travel range of 300mm. The position of the objective is adjusted via the specific application software APT provided with the translation stage. It is used to ensure that the focal planes of objective and test lens always coincide. The test lens is placed in a horizontal configuration, i.e. with its optical axis oriented vertically.

The reference beam passes straight through BS1 and is subsequently recombined with the measurement beam at the second non-polarizing beam splitter (BS013, 1", 400 – 700nm, 50:50 intensity split ratio, BS2).

After recombination at BS2 half of the light falls onto a CCD camera (uEye, UI-1225LE-M-HQ, C1) placed behind BS2. This camera is used for the interferometric alignment of the light passing through the reference and the measurement arm. An optical shutter (OS1) between BS1 and BS2 allows to block the beam from BS1 during the SHWS measurement.
The second half of the recombined beam is expanded using a relay system, comprised of two bi-convex lenses (RL1 and RL2) of focal lengths $f_1 = 50 \, \text{mm}$ and $f_2 = 50 \, \text{mm}$, separated by a distance of mm. The relay system magnifies the beam size by a factor of two. It also ensures that the outgoing beam from RL2 remains parallel to the beam entering RL1 without experiencing any convergence or divergence with respect to the original beam. This beam then falls onto the CCD ($5.75 \times 4.76 \, \text{mm}^2$) of the Shack-Hartmann wavefront sensor (WFS150-7AR, SHWS). Moreover, the relay system ensures that the beam illuminates a sufficient number of lenslets on the SHWS to achieve an accurate measurement.

4. Results and discussion

Experiments are performed as follows: Initially, all voltages are set to zero. This implies that the aqueous drop assumes a shape of constant mean curvature consistent with the boundary conditions imposed, i.e. the contact angles on bottom plate and on the bottom of the aperture plate, contact line pinning along the aperture, and the fixed volume that was injected. There are thus two separated liquid-oil interfaces that are in mechanical equilibrium, namely the actual refracting lens surface above the aperture and the annular interface between the aperture plate and the bottom plate. In mechanical equilibrium both of these interfaces have the same constant mean curvature. For $U_{as} = 0$, the lens surface is a spherical cap, as shown by side view images in a previous publication with a more open geometry allowing for side view imaging [15]. (The Bond number $Bo = \Delta \rho g R^2 / \gamma = 0.175$ ( $\Delta \rho$ : density difference oil-water; $g$ : gravitational acceleration), which specifies the ratio between gravitational effects and surface tension suggests that there should be some gravitational flattening at zero voltage, which would enhance the spherical aberration. Yet, even if present, this effect can be compensated by the Maxwell stress upon applying a voltage.) The other oil-water interface has the shape of a cylindrically symmetric Delaunay surface, typically an unduloid or a nodoid, depending on the pressure drop across the interface [23] and hence on the control parameter $U$, that controls the contact angle on the bottom plate. The device is tolerant against variations in the total liquid volume. More or less volume simply leads to a larger or smaller radius of the sandwiched part of the drop between the bottom and aperture plates. Such variations do not affect the shape of the refracting surface. This is a substantial practical advantage compared to other approaches in optofluidic applications, where a few percent of overfilling or underfilling of liquid can have substantial effects on the device characteristics and performance [24].

![Fig. 3](image_url)

**Fig. 3.** Focal length (a) and primary asphericity (Zernike coefficient $Z^0$) (b) vs. the pressure-controlling electrowetting voltage recorded for $U_{as} = 0$. Red: increasing voltage. Black: decreasing voltage.
Variations of the EW voltage \( U \) change the contact angle on the bottom plate and thereby also the curvature of the annular part of the drop surface. As a consequence, the radius of the lens surface and hence the focal length of the device change. For the present device, varying \( U \) between 0 and 70V leads to a perfectly reversible variation of the focal length between approximately 10mm and 27mm, as shown in Fig. 3a. In these experiments, the focal length is measured using the SHWS. After applying a voltage to the device, the microscope objective in the measurement arm is displaced until the Zernike coefficient corresponding to defocusing (\( Z_4^1 \) or Z4) is minimized. (We consider the wavefront on the SHWS as flat if its radius of curvature exceeds 20m.) The corresponding displacement is noted as the variation of the focal length. At the same time, all other Zernike coefficients are measured using the SHWS. Figure 3b shows the corresponding variation of the primary spherical aberration \( Z_4^1 \).

(We use here the indexing based on the radial (subscript) and azimuthal (superscript) degree of the Zernike function. According the OSA standard, this coefficient would be denoted as Z12; according to Noll Z11; and according to the popular ray-tracing software package Zemax as Z13.) As expected given the spherical shape and the fixed aperture diameter, the
spherical aberration is maximum at zero voltage, i.e. for the shortest focal length and decreases monotonically as the focal length increases. Again, the observed variation is perfectly reversible. The latter is to be expected because the edge of the lens is pinned to the edge of the aperture and only the free liquid surface deforms. Figure 4a shows a few typical wavefronts as measured through the spherical lens for the shortest focal lengths investigated.

Subsequently, we varied the voltage \( U_a \) on the top plate to reduce the asphericity of the lens for a series of fixed values of \( U_r \). For each configuration, the focal length and the Zernike coefficients were determined following the same protocol as described above. As shown in Fig. 5a, the focal length decreases with increasing \( U_a \) for every fixed value of \( U_r \). At the same time, the liquid surface becomes increasingly aspherical and the corresponding Zernike coefficient for primary asphericity \( (Z^p_0) \) decreases. Because \( Z^p_0 \) is maximum for the shortest focal length \( (U_r = 0) \) the reduction in asphericity is most pronounced under these conditions. Over the whole range of focal lengths from 10mm to 27mm, it was possible to achieve values of \( Z^p_0 < 0.005 \lambda \) (Fig. 5b). Likewise, the simultaneously recorded Zernike coefficient of the secondary asphericity remained at low levels \( Z^p_0 < 0.005 \lambda \) for all voltages applied. Images of wavefronts of minimum asphericity are shown in Fig. 4b for the three lowest values of \( U_r \).

![Fig. 5. Variation of focal length (a) under zero defocus condition and primary asphericity (Z^p_0)(b) vs. lens voltage U_a. Symbol colours indicate variable U_r, increasing along the arrows: 0V(black squares), 10V(red circles), 20V(blue up triangles), 30V(pink down triangles), 40V(green diamonds), 50V(dark blue left triangles), 60V(purple right triangle), 70V(orange hexagon).](image)

Like in the case of varying \( U_r \) at fixed \( U_a \), both asphericity and focal length are thus affected at the same time. This is caused by the overall attractive force that the top plate exerts on the drop surface. The resulting total force has to be compensated by an increasing average Laplace pressure, which results in an increasing average curvature of the lens and hence a shorter focal length. Varying the focal length while keeping the asphericity minimal thus requires a coordinated simultaneous variation of both control voltages, similar to the results presented earlier with a hydrostatically controlled back pressure [15]. In contrast to the previous mechanical system, the present purely electrically controlled device allows for simultaneous electrical control such that it becomes possible to keep a fixed desired value of, say, the asphericity, while changing the focal length, or vice versa.

The present device was not optimized in any specific direction regarding the choice of the fluid, except for the fact that we wanted to demonstrate a positive spherical aberration that would be reduced. Different choices of liquid (in particular larger differences in refractive indices) will result in wider tuning ranges of the spherical aberration. Similarly, the tuning
range of the focal length could be increased by choosing a different ratio between the aperture diameter and the spacing between the middle and bottom plate. We note, however, that the presently achieved tuning range already exceeds the one demonstrated e.g. for elastomeric lenses with tunable geometric aberrations [8]. Clearly, combining the present approach with an array of structured electrodes on the top plate instead of the homogeneous one described here would enable systematic addressing of other geometric aberrations such as coma and astigmatism in arbitrary directions [16,17]. Moreover, it is conceivable to include a feedback mechanism to the electrical actuation. In this manner, the system could be used to actively control the shape of the wavefront and to further optimize imaging properties e.g. within a confocal microscope. The response speed of our lens is determined by the hydrodynamic response time of the drop, which scales with the aperture diameter \(D^{3/2}\). Although not tested explicitly in the work, we expect for the dimensions of the present device that this time will be of the order of a few tens of ms [5]. It can be increased substantially, if smaller aperture diameters are acceptable [19].

5. Conclusion

The integration of an electrowetting based pressure control in a liquid lens and an additional Maxwell stress controlled deformation of the refracting liquid-liquid interface leads to an all electrically controlled tunable optofluidic lens with a wide range of reversibly tunable focal length and asphericity. This all electrical control is expected to enable the implementation of feedback mechanisms for adaptive wavefront shaping, which is particularly attractive in combination with segmented electrodes that allow to address specific primary aberrations in a targeted manner.

Funding

Dutch Science Foundation NWO Foundation for Technical science STW, VICI program 11380.

Acknowledgments

We thank Daniel Wijnperle of PCF Twente for fabricating Teflon-coated ITO slides and Daniel Koop and Prof. Dr. Hans Zappe of the University of Freiburg for assistance with designing the optical setup.

Disclosures

The authors declare that there are no conflicts of interest related to this article.

References

1. P. Minzioni, R. Oselzame, C. Sada, S. Zhao, F. G. Omenetto, K. B. Gyflason, T. Haraldsson, Y. B. Zhang, A. Ozcan, A. Wax, F. Mugele, H. Schmidt, G. Testa, R. Bernini, J. Guck, C. Liberale, K. Berg-Sorensen, J. Chen, M. Pollnau, S. Xiong, A. Q. Liu, C. C. Shiue, S. K. Fan, D. Erickson, and D. Sinton, “Roadmap for optofluidics,” J. Opt. 19(9), 093003 (2017).
2. C. P. Chiu, T. J. Chiang, J. K. Chen, F. C. Chang, F. H. Ko, C. W. Chu, S. W. Kuo, and S. K. Fan, “Liquid Lenses and Driving Mechanisms: A Review,” J. Adhes. Sci. Technol. 26(12-17), 1773–1788 (2012).
3. N. T. Nguyen, “Micro-optofluidic Lenses: A review,” Biomicrofluidics 4(3), 031501 (2010).
4. C. A. Lopez and A. H. Hirsa, “Fast focusing using a pinned-contact oscillating liquid lens,” Nat. Photonics 2(10), 610–613 (2008).
5. B. Berge and J. Peseux, “Variable focal lens controlled by an external voltage: An application of electrowetting,” Eur. Phys. J. E 3(2), 159–163 (2000).
6. T. Krupenkin, S. Yang, and P. Mach, “Tunable liquid microlens,” Appl. Phys. Lett. 82(3), 316–318 (2003).
7. S. Kuiper and B. H. W. Hendriks, “Variable-focus liquid lens for miniature cameras,” Appl. Phys. Lett. 85(7), 1128–1130 (2004).
8. P. Liebetraut, S. Petsch, J. Liebeskind, and H. Zappe, “Elastomeric lenses with tunable astigmatism,” Light Sci. Appl. 2(9), e98 (2013).
9. P. Zhao, Ç. Ataman, and H. Zappe, “Spherical aberration free liquid-filled tunable lens with variable thickness membrane,” Opt. Express 23(16), 21264–21278 (2015).
10. D. Kopp and H. Zappe, “Tubular astigmatism-tunable fluidic lens,” Opt. Lett. 41(12), 2735–2738 (2016).
11. M. Zohrabi, R. H. Cormack, C. Mccullough, O. D. Supekar, E. A. Gibson, V. M. Bright, and J. T. Gopinath, “Numerical analysis of wavefront aberration correction using multielectrode electrowetting-based devices,” Opt. Express 25(25), 31451–31461 (2017).
12. Z. Zhan, K. Wang, H. Yao, and Z. Cao, “Fabrication and characterization of aspherical lens manipulated by electrostatic field,” Appl. Opt. 48(22), 4375–4380 (2009).
13. G. Manukyan, J. M. Oh, D. van den Ende, R. G. H. Lammertink, and F. Mugele, “Electrical Switching of Wetting States on Superhydrophobic Surfaces: A Route Towards Reversible Cassie-to-Wenzel Transitions,” Phys. Rev. Lett. 106(1), 014501 (2011).
14. J. M. Oh, G. Manukyan, D. van den Ende, and F. Mugele, “Electric-field-driven instabilities on superhydrophobic surfaces,” EPL 93(5), 56001 (2011).
15. K. Mishra, C. Murade, B. Carreel, I. Roghair, J. M. Oh, G. Manukyan, D. van den Ende, and F. Mugele, “Optofluidic lens with tunable focal length and asphericity,” Sci. Rep. 4(1), 6378 (2014).
16. N. C. Lima, A. Cavalli, K. Mishra, and F. Mugele, “Numerical simulation of astigmatic liquid lenses tuned by a stripe electrode,” Opt. Express 24(4), 4210–4220 (2016).
17. N. C. Lima, K. Mishra, and F. Mugele, “Aberration control in adaptive optics: a numerical study of arbitrarily deformable liquid lenses,” Opt. Express 25(6), 6700–6711 (2017).
18. K. Mishra and F. Mugele, “Numerical analysis of electrically tunable aspherical optofluidic lenses,” Opt. Express 24(13), 14672–14681 (2016).
19. C. U. Murade, D. van der Ende, and F. Mugele, “High speed adaptive liquid microlens array,” Opt. Express 20(16), 18180–18187 (2012).
20. C. Li, G. Hall, X. Zeng, D. Zhu, K. Eliceiri, and H. Jiang, “Three-dimensional surface profiling and optical characterization of liquid microlens using a Shack-Hartmann wave front sensor,” Appl. Phys. Lett. 98(17), 171104 (2011).
21. Y. T. Tung, C. Y. Hsu, J. A. Yeh, and P. J. Wang, “Measurement of Optical Characteristics in Dielectric Liquid Lens by Shack-Hartmann Wave Front Sensor,” in Novel Optical Systems Design and Optimization Xv, G. G. Gregory and A. J. Davis, eds. (2012).
22. F. Mugele and J. Heikenfeld, Electrowetting: Fundamental Principles and Practical Applications (Wiley-VCH, Weinheim, Germany, 2019).
23. R. Finn, Equilibrium capillary surfaces (New York [u.a.] Springer, 1986).
24. I. Roghair, M. Musterd, D. van den Ende, C. R. Kleijn, M. Kreutzer, and F. Mugele, “A numerical technique to simulate display pixels based on electrowetting,” Microfluid. Nanofluidics 19(2), 465–482 (2015).