Electrically tunable optofluidic lenses: Fabrication and Characterization

Kartikeya Mishra
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Chapter 1

Introduction to liquid lenses

1.1 Introduction

Fluids have a remarkable property of adapting to any shape and configuration. They can be altered into any desired configuration as per the requirement. Unlike solids, fluids are much more responsive and amenable to morphological transition, when subjected to any external stimuli like electric field, hydrostatic pressure etc. The degree of change, induced in the configuration can also be controlled by the potency of the driving stimuli. Moreover, physical properties of liquids can be easily altered by number of mechanisms. For example, refractive index of liquids can be easily manipulated by dissolving an appropriate solute. The change in the refractive index can also be controlled by adjusting the dosing amount of the solute. This is stark contrast to the solid state behavior, wherein, once manufactured, the refractive index, determined by the very nature of lens material, cannot be further conditioned. These remarkable properties of fluids makes them a fit choice in various lensing applications.

Lenses are the essential components of any optical design and are an integral part of any optical setup. Lenses, however come with their own intrinsic imperfections, called optical aberrations. Such imperfections pose a fundamental challenge to imaging optics. The aberrations present in any optical system degrade the optical quality of image, rendering the optical system inappropriate for many commercial applications. Consequently, it is always desirable to manufacture lenses free from aberrations. Several techniques have been devised to amend their efficiency and improve their performance for upgrading the imaging standards. Adaptive optics is one such specialized technique to address the limitations of conventional optical system. Conventional optical systems involve the use of multiple optical elements for mutually cancelling out the aberrations due to each optical element, thereby enhancing the optical performance of the overall optical unit. In order to achieve best optical output, inter element distance between optical components needs to be altered as each lens has a fixed focal length. This makes a conventional optical system demanding in terms of number of optical elements required and also in managing the interplay between them. Subsequently, it calls for designing high quality lenses as individual optical entity, with superior optical metrics.

Lenses exhibiting higher resolution are much sought for imaging applications. However, the downside is their fixed focal length and hence fixed numerical aperture. Once casted, their shape can no longer be altered and their configuration is freezed in time. Non-tunability of solid lenses is a bottleneck, rendering them suitable only for a particular
application requiring a specific focal length with particular set of optical properties. This invokes the notion of using fluids as a substitute for regular solid lenses. The fusion of optics and fluidics gives us countless opportunities to modulate the liquid droplet shapes for facilitating different optical needs.

Optofluidic lenses, in this context have the potential to push the frontiers in imaging applications due to their tunable nature and due to their ability to correct optical aberrations. The liquid lens technology also offers whole host of opportunities wherein it can be a potential substitute for cumbersome multi-element optical system. Liquid lenses, being tunable in nature, can replace the individual elements, thereby simplifying the complex structure of any optical system and reducing its overall size and weight. However, at the same time, there are also severe limitations regarding their fabrication technology, mechanical stability and robustness. We shall discuss in detail the fabrication and working of different kinds of optofluidic lenses and shall elaborate on the various tuning mechanisms for altering the lens configuration in the forthcoming chapters, particularly focusing on the use of electric field.

1.2 Motivation

The motivation of this thesis stems from the simulation results reported by Oh.et.al.[1]. It was shown that a liquid-air interface, when subjected to electric field, undergoes aspherical deformations producing interface shapes of varying eccentricities. In this thesis, we construct and characterize optofluidic lenses of tunable focal length and asphericity, demonstrating superior optical quality. Starting from spherical meniscus at zero voltage, one can tune the morphology of lens meniscus to any desired configuration at a finite voltage. It is well documented in lens literature that a perfect lens is obtained when eccentricity of the lens meniscus matches the refractive index ratio of lens fluid to that of ambient medium[2]. Such a hyperbolic profile with eccentricity greater than one, acts as an ideal lens, completely devoid of any spherical aberration. This holds true when object is at infinity, as measured from the optical center of the lens and rays falling on the lens surface are parallel to the optical axis. An application of electric field to liquid-liquid interface opens immense possibilities for fabricating optofluidic lenses with tunable focal lengths and provides a viable alternative to the limitations posed by solid lenses. Here, we shall particularly address the problem of spherical aberration, inherent to the liquid spherical lenses, and propose a possible solution to suppress the same. Spherical aberration, if present, mars the optical quality of the captured image and renders the lens useless in high resolution imaging applications. We employ electric field as a tool to manipulate the asphericity of the lens meniscus. Further, by employing two different pressure control mechanisms, namely, electric field and electrowetting or electric field and hydrostatic pressure, one can independently tune the focal length and asphericity.

1.3 Thesis Outline

Chapter 2 highlights the recent developments in the domain of optofluidic lens technology. It presents a literature survey about the advancements in the different fabrication techniques of the liquid lenses and discusses various pressure mechanisms to produce lens shapes of
different configurations, namely: spherical, aspherical and cylindrical. It also presents a perspective on the pros and cons of electric field over other driving mechanisms like hydrostatic pressure, pneumatic driving etc.

Chapter 3 delineates the standard tools and methodologies to characterize the optical lenses. It enlists various schemes of geometrical ray-tracing as well as wavefront characterization of liquid lenses by employing regular benchmark techniques. It explains the origin and cause of optical aberrations, further elucidating on the mathematical foundations of wavefront aberration function and its subsequent representation by Zernike polynomials. Other optical metrics determining the standards of optical performance like MTF, spot diagrams and Strehl’s ratio are also vividly discussed. Optical simulation platform, Zemax is also described in detail starting from building an optical model to analysis of the optical aberrations.

In chapter 4, we demonstrate the use of two pressure controllers: electric field and hydrostatic pressure to produce optofluidic lenses of varying asphericity and focal lengths. Hydrostatic pressure is used to control the initial curvature of the lens meniscus while electric field is used to induce asphericity. It was shown that longitudinal spherical aberration (LSA) can be suppressed as the shape of lens meniscus translates from spherical at zero voltage to parabola and further to hyperbola at higher voltages. LSA is completely eliminated when the eccentricity of the meniscus profile matches the refractive index ratio of the lens fluid to that of ambient medium. The analysis is corroborated by imaging a square grid. It shows considerable spherical aberration and distortion when imaged through a spherical lens at zero voltage. However, as the voltage is raised, spherical aberration is largely suppressed and flat topography of the square grid is restored, indicating elimination of distortion.

In chapter 5, we exploited the optical simulation tool Zemax to simulate the lens setup as described in chapter 4. We evaluated the standard optical parameters like MTF, RMS spot size and Strehl’s ratio to gauge the optical performance of our optofluidic lens in real world environment. The study investigates the optical quality of the liquid lenses on the basis of wavefront aberrations. The simulation results further validates the experimental outcomes of chapter 4. It was observed that for perfect lens MTF curve essentially overlaps the diffraction limited curve demonstrating higher resolution indicated by high Strehl’s ratio, close to 0.99 and spot diagram contained entirely within the confines of airy disc.

Chapter 6 outlines the construction and working of optical setup used for wavefront characterization of optofluidic lens device. It explains the underlying principles of optical alignment and enunciates step by step procedure detailing the building of setup from scratch. We shall also discuss the operating principle of Shack Hartmann Wavefront Sensor (SHWS) and its application in determining the Zernike aberration coefficients. Finally, we compare the experimental results of two plano-convex test lenses with the simulation results of Zemax. The close overlap between the two illustrates the authenticity of our experimental setup.

Chapter 7 comprises the fabrication and wavefront characterization of a purely electrically actuated optofluidic lens device. We presented a detailed account of building a robust, portable, leak-proof and compact fluidic lens device. The device is amenable to optical
characterization by standard benchmark techniques like wavefront characterization by Shack Hartmann Wavefront Sensor (SHWS). Unlike in chapter 4, initial curvature was regulated by electrowetting instead of hydrostatic pressure. Zernike spherical aberration is experimentally evaluated under zero defocus condition. The electrowetting reversibility is confirmed by reproducibility of focal lengths and Zernike spherical aberration coefficients (Z13) as electrowetting voltage is tuned back and forth from 0 to 70V. We further demonstrated that spherical aberration can be reduced and can be eventually eliminated by application of voltage between the aperture plate and top electrode, as manifested in the zeroth value of Z13.

Chapter 8 includes the concluding remarks and enlists the various possibilities of further exploiting the lens device for creating astigmatic lenses. We also present a future perspective about the flexible use of the device by employing multiple stripe electrodes for producing arbitrary meniscus shapes which can cater to different industrial applications. By selectively switching the electrodes, one can create aspherical, astigmatic and comatic lenses.

References

Chapter 2

Recent developments in optofluidic lens technology

Abstract

Optofluidics is a rapidly growing versatile branch of adaptive optics including a wide variety of applications such as tunable beam shaping tools, mirrors, apertures, and lenses. In this review, we focus on recent developments in optofluidic lenses, which arguably forms the most important part of optofluidics devices. We report first on a number of general characteristics and characterization methods for optofluidic lenses and their optical performance, including aberrations and their description in terms of Zernike polynomials. Subsequently, we discuss examples of actuation methods separately for spherical optofluidic lenses and for more recent tunable aspherical lenses. Advantages and disadvantages of various actuation schemes are presented, focusing in particular on electrowetting-driven lenses and pressure-driven liquid lenses that are covered by elastomeric sheets. We discuss in particular the opportunities for detailed aberration control by using either finely controlled electric fields or specifically designed elastomeric lenses.
2.1 Introduction

Micro-optics is ubiquitous in the industry and has numerous applications in many domains, such as construction of fiber optics, mobile phone cameras, CD players, military equipment, and other consumer goods. The functionality of these devices is usually constrained by their fixed focal length and, thus, their inability to access objects present at different distances from the device. Adaptive optics offers a viable solution to this limitation. Adaptive optics can modulate the configuration of an optical surface by an external stimulus, such as an electric field, fluidic pressure, etc. This modulation enhances the operating range of a device by increasing the span of the device’s focal length, thus enabling it to scan objects present at varying distances. During the past few years, such miniaturized adaptive optical systems catering to the growing challenges posed by conventional optical systems have increased. The discipline is rich and diverse and is constituted by liquid crystals, deformable soft materials, and deformable liquids, such as optofluidics. Extensive reviews of various optofluidic systems, their utilities, and applications [1–5] are available. The advent of such optofluidic devices has provided an alternative route to re-designing and improving pristine optical systems. Such devices offer greater flexibility, supplemented by microscopic accuracy. This review focuses on a specific subset of optofluidics, namely optofluidic lenses. Such lenses have attracted considerable attention in the recent past as they are especially suited for use in adaptive optics to enhance optical performance. They have been at the epicenter of this technological innovation. A detailed review [6] is available that broadly covers the essential aspects of lens design, fabrication, and optical characterization. Optofluidic lenses come in several types: pure liquid lenses with only free liquid surfaces, liquids coated with thin elastomeric membranes, and polymeric lenses. The liquid lens literature largely deals with spherical lenses. Various techniques and tuning mechanisms have been explored to create liquid lenses, including pressure variation, thermal expansion, and electrowetting. Electrowetting (EW) has emerged as a powerful tool for manipulating the liquid–liquid interface [7–11]. The phenomenon has been explored to produce liquid lenses with various morphological configurations. Berge et al. [7] employed EW for the first time to produce spherical lenses of varying focal lengths by altering the contact angle. EW was also used by Kuiper et al. [8] to manipulate the liquid–liquid interface as a functioning optical lens. A similar approach was adopted by Kruipenkin et al. [9] to change the liquid lens curvature. Other noted mechanisms of tuning liquid lenses are hydrodynamic actuation [12], thermal stimulation [13–15], etc. These mechanisms are discussed in detail in subsequent sections. However, these driving mechanisms retain the spherical character of liquid lenses, rendering them prone to spherical aberration. The presence of such aberrations hampers the image quality, adversely affecting the optical performance. Non-spherical shapes are thus highly desirable to minimize aberrations and to improve image resolution. Consequently, several experimental techniques for inducing non-sphericity have been formulated. In a review article, Hung et al. [16] summarized the progress made in the fabrication techniques for producing aspherical polymeric microlenses with a high numerical aperture and the requested spot size. Roy et al. [17] designed and fabricated an optofluidic aspherical lens
employing the Elastocapillary effect. Elastomeric lenses, an alternative to liquid lenses, with tunable astigmatism have also been reported [18]. Such lenses may have applications in correcting ocular astigmatism. Liebetraut et al. [19] gave an abridged account of the optical properties of various liquids used to fabricate optofluidic lenses. Another class of lenses, called gradient refractive index (GRIN) lenses, is also used in optical applications. The variation in the refractive index of the lens material is used to focus the incoming light beam. Mao et al. [20] reported the design and functioning of a tunable liquid gradient refractive index lens (L-GRIN lens) by optimally controlling the diffusion of calcium chloride, as the solute, in water. The concentration gradient of calcium chloride results in continuous variation in the refractive index along the concentration profile, enabling the targeted focusing of the laser beam when impinged on the mixing channel. Chen et al. [21] fabricated focus tunable laser induced 2D-GRIN liquid lenses. The device consists of two chromium strips for heating the enclosed lens fluid. By varying the laser intensity, thermal gradients are induced in both transverse and longitudinal directions, thereby modulating the lens shape. Such lenses offer aberration-free imaging and low actuation times, typically 200 ms. Fluidic lenses can be broadly categorized into three types of shape: spherical, aspherical, and cylindrical. In each case, we discuss the working principle and device architecture of the lens system. We further sub-classify each lens based on its actuation mechanism. Special attention will be given to two important aspects of aspherical lenses: tunability and aberration control.

This review is organized as follows: In Section 2, we provide an overview of the general characteristics of optofluidic lenses, including, in particular, a discussion on lens aberration. Section 3 focuses on the various concepts of adaptive spherical lenses, with an emphasis on EW-controlled liquid lenses. In Section 4, we discuss various approaches for controlling aberrations by generating non-spherical lens shapes. Finally, in Section 5, we discuss several optofluidics concepts in addition to lensing applications.

2.2 General Characteristics of Optofluidics Lenses

2.2a Liquid Lens Shapes and Actuation Principles

According to Laplace’s law, free liquid surfaces in mechanical equilibrium and in the absence of other forces display a constant mean curvature \( \kappa \). The curvature is related to a pressure drop \( \Delta P \) across the interface by:

\[
\Delta P = 2 \kappa \gamma
\]

where \( \gamma \) is the surface tension of the liquid. If the system is cylindrically symmetric, this results in a spherical cap shape with a radius \( R \) that is given by the inverse of the mean curvature, i.e., \( R = 1/\kappa \). Unlike solid surfaces that have to be machined very carefully to be at the same time perfectly spherical on a global scale and perfectly smooth on a small scale of, say, \( \lambda/10 \) (\( \lambda \): typical wavelength of visible light), liquid surfaces in equilibrium are thus perfectly spherical and perfectly smooth by the laws of physics. While some intrinsic roughness due to thermally excited fluctuating capillary waves is present in principle, the
resulting roughness amplitude is no larger than $O(1 \text{ nm})$, thanks to the strength of typical interfacial tensions ($O(\text{tens of } \text{mN/m})$). In this sense, liquids are ideal materials to fabricate lenses. In addition, free liquid surfaces are perfect for adaptive optics because their refractive power, which scales as the inverse of the radius of the liquid lens, can simply be adjusted by controlling the pressure between the lens fluid and the ambient medium following Equation (2.1). We will denote such lenses as free interface liquid lenses, FI-LLs.

Several important caveats apply, though. Some of them are exclusively disadvantageous; others also offer opportunities for additional functionality, in particular aberration control. First, many liquids tend to evaporate, which would make any device useless. To circumvent evaporation, liquid lenses are generally designed from two immiscible liquids, such as water and oil, both contained in a sealed container. Once the ambient fluid is saturated with the lens fluid, the lens volume remains constant. Alternatively, the liquid droplet can be covered by a thin elastomeric membrane that is impermeable to the lens fluid. We will denote such lenses as elastomeric membrane liquid lenses, EM-LLs. Frequently, such membranes are made of polydimethylmethoxysilane (PDMS) with a thickness varying from several tens to a few hundred micrometers. The membranes not only suppress evaporation, they also provide a lot more stiffness to the liquid lens because the surface tension in Equation (2.1) is essentially replaced by the elastic tension of the membrane. One should note, though, that this comes at the expense of introducing an additional layer of a material into the optical path, which—unlike the liquid surface—is no longer automatically smooth by the laws of physics. Moreover, the thickness of such a layer also needs to be carefully controlled to be perfectly homogeneous—or laterally modulated in a perfectly controlled manner, if desired otherwise.

Second, liquid surfaces are only perfectly spherical as long as other external forces are negligible. Additional external forces such as gravity lead to deviations from the spherical shape. In the presence of gravity, Equation (2.1) must be extended by an additional hydrostatic pressure $\Delta P_h = \Delta \rho g z$, where $\Delta \rho = \rho_l - \rho_a$ is the difference between the density of the lens fluid $\rho_l$ and the density of the ambient fluid $\rho_a$, $g$ is the gravitational acceleration, and $z$ is the height above the reference level, for which $\Delta P = 2 \kappa_y$. The corresponding equation then reads:

$$P = 2 \kappa_y + \Delta \rho g z$$  \hspace{1cm} (2.2)

Equation (2.2) states that $\kappa = \kappa(z)$ in the presence of gravity is no longer constant. If we use the radius of curvature $R$ of the lens as characteristic length scale and the Laplace pressure $P_L = \gamma/R$ as the characteristic pressure scale, Equation (2.2) can be rewritten in non-dimensional form as:

$$\Delta \bar{P} = \kappa + Bo \bar{z}$$  \hspace{1cm} (2.3)

where $Bo = \Delta \rho g R^2 / \gamma$ is the Bond number, and $\Delta \bar{P} = \Delta P / P_L$, $\kappa = 2 R \kappa$, and $\bar{z} = z / R$. This implies that the contribution of gravity is negligible provided that $Bo \ll 1$ or, equivalently,
$R \ll \lambda_c$, where $\lambda_c = \frac{Y}{\sqrt{\Delta \rho g}}$ is the capillary length. For water in air, $\lambda_c \approx 2.7$ mm. To achieve spherical shapes on larger scales, it is necessary to minimize the density difference between the lens liquid and the ambient liquid. By choosing suitable oils and water and additives, it is possible to reduce $\Delta \rho$ to $\approx 10^{-3}$ g/cm³. Density matching between the lens liquid and the ambient liquid not only minimizes the effect of gravity, it also minimizes the sensitivity of the lens to ambient vibrations. A liquid lens system with perfectly density matched fluids is completely insensitive to accelerations, making such a design superior to any mechanical system with translatable solid lenses.

Like oil–water density matching, covering the lens by an elastomeric membrane also provides superior stability against both gravitational distortion and vibrations. In this case, the enhanced stability arises from the much higher membrane tension that qualitatively replaces the surface tension. It should be noted, though, that quantitatively the resulting relation between the excess pressure (or mechanical stresses applied in other manners) and the lens curvature is usually more complex because the devices are often deformed to substantial strains, leading to non-linear elastic response.

Notwithstanding this sometimes complex non-linear elastic response, the general approach to achieve tunability is the same for both FI-LLs and EM-LLs: an excess mechanical pressure or stress deforms the shape of the lens—and subsequently refraction of light from the variable lens shape provides optical tunability. If the deformation is simply achieved by increasing a hydrostatic pressure, the resulting lens will typically remain spherical. There are, however, opportunities to achieve non-spherical deformations, too. In the case of FI-LLs, arbitrary non-spherical surface shapes can be achieved if the liquid surfaces are deformed by non-homogeneous external fields, such as electric fields, which we will discuss in Section 4. For EM-LLs, asymmetric stresses and/or asymmetric thickness profiles of the membranes can provide access to non-spherical lens shapes (see also Section 2.4).

### 2.2b Quantification of Optical Aberrations and Lens Shapes

Optical aberrations hamper the quality of optical images. Aberrations can be quantified by analyzing the wavefront emanating from a particular optical system. The shape of the emanating wavefront is completely determined by the refractive properties of the optical systems, i.e., by the shape of the lens(es) for homogeneous optical materials. For a single lens, this one-to-one correlation allows us to reconstruct the shape of the lens from the wavefront. It is customary to represent wavefronts as a superposition of Zernike polynomials, an infinite and complete set of orthonormal polynomials defined on a unit circle. The amplitude of each Zernike polynomial determines the strength of the corresponding aberration. There are several manners of numbering Zernike polynomials, depending on their number of nodes and azimuthal symmetry. Table 2.1 provides a list of the most common optical aberrations and the corresponding Zernike polynomials [22]. For example, spherical aberration describes the non-uniform refractive power of rotationally symmetric spherical lenses: off-axis beams are refracted more strongly than paraxial beams, resulting in a radius-dependent focal length. Non-rotationally symmetric lenses may have
different curvatures in perpendicular directions, the tangential and the sagittal plane, causing astigmatic or cylindrical aberration. Imaging a point object through an astigmatic lens produces a line image. Coma results in an off-axis location of the focus of a lens.

<table>
<thead>
<tr>
<th>Index</th>
<th>Radial Nodes (n)</th>
<th>Azimuthal Index (m)</th>
<th>Type of Aberration</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>piston</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>1</td>
<td>X-tilt (tip)</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>−1</td>
<td>Y-tilt (tilt)</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>0</td>
<td>Defocus</td>
</tr>
<tr>
<td>5</td>
<td>2</td>
<td>−2</td>
<td>Oblique astigmatism</td>
</tr>
<tr>
<td>6</td>
<td>2</td>
<td>2</td>
<td>Vertical astigmatism</td>
</tr>
<tr>
<td>7</td>
<td>3</td>
<td>−1</td>
<td>Vertical coma</td>
</tr>
<tr>
<td>8</td>
<td>3</td>
<td>1</td>
<td>Horizontal coma</td>
</tr>
<tr>
<td>9</td>
<td>3</td>
<td>−3</td>
<td>Vertical trefoil</td>
</tr>
<tr>
<td>10</td>
<td>3</td>
<td>3</td>
<td>Oblique trefoil</td>
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<td>0</td>
<td>Primary spherical</td>
</tr>
<tr>
<td>12</td>
<td>4</td>
<td>2</td>
<td>Vertical secondary</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>astigmatism</td>
</tr>
<tr>
<td>13</td>
<td>4</td>
<td>−2</td>
<td>Horizontal secondary</td>
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<td>astigmatism</td>
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<tr>
<td>14</td>
<td>4</td>
<td>4</td>
<td>Vertical quadrafoil</td>
</tr>
<tr>
<td>15</td>
<td>4</td>
<td>−4</td>
<td>Oblique quadrafoil</td>
</tr>
</tbody>
</table>

Table 2.1. Classification of Zernike polynomials and corresponding optical aberration. Even and odd Zernike polynomials are defined as $Z_n^m = R_n^m(\rho)\cos(m\phi)$ and $Z_n^m = R_n^m(\rho)\sin(m\phi)$, where $\rho$ and $\phi$ are the radial and azimuthal coordinate and $R_n^m(\rho) = \sum (-1)^k(n-k)! \left[ k! \left( \frac{n+m}{2} - k \right)! \left( \frac{n-m}{2} - k \right)! \right] \rho^{n-2k}$ is the radial function for $(n-m) \geq 0$ and even. The sum runs from 0 to $(n-m)/2$. For $(n-m)$ odd: $R_n^m \equiv 0$.

The complete set of Zernike coefficients obtained with this decomposition characterizes all optical aberrations of the lens, such as. The larger the Zernike coefficient, the larger is the corresponding aberration.

The most popular and ubiquitous instrument for this type of lens characterization is the Shack–Hartmann wavefront sensor (SHWS) [23]. A SHWS allows us to reconstruct the distortion of a wavefront from the deflections of the focus positions of an array of microlenses on a CCD (charge coupled device) sensor. The 3D wavefront is re-constructed from these focus positions using inbuilt numerical algorithms. From the aberrations measured by a SHWS, it is also possible to calculate the surface profile of the lens in three dimensions, as shown by Li et al. [24] for liquid microlenses.

Throughout this review, we will pay particular attention to cylindrically symmetric lenses, for which primary spherical aberrations are the most important aberration. The ideal shape of a cylindrically symmetric lens transforming light emitted from a point source into plane waves is a hyperbola with an eccentricity $e = n_t/n_a > 1$, where $n_t$ and $n_a$ are the
refractive indices of the lens material and of the ambient medium. With ideal lens shapes being derived from conic sections, it has become customary to characterize the shape of general rotationally symmetric aspherical lenses by the equation:

$$z(r) = \frac{r^2}{R \left( 1 + \sqrt{1 - (1 + K) \frac{r^2}{R^2}} \right)} + \alpha_4 r^2 + \alpha_6 r^4 + \alpha_8 r^6 + \ldots$$  \hspace{1cm} (2.4)$$

where $r$ is the radial coordinate and $z$ the axial position of the lens surface. The first term in Equation (2.4) describes the ideal conic section with the conic constant $K = -\kappa^2$ and the radius of the lens apex $R$. The other terms describe deviations from the ideal conical shape with ‘aspherical coefficients’ $\alpha_i$ of the symmetric algebraic terms in $r$. Conic lenses are a subset of aspherical lenses, with all $\alpha_i = 0$. The eccentricity is zero for spherical lenses, unity for parabolics, between zero and unity for elliptical lens, and greater than unity for hyperbolic lenses. For $K = 0$ and $\alpha_i = 0$, the equation is reduced to that of a sphere signifying spherical lenses. These lenses have spherical aberrations, which implies that off axis marginal rays entering the lens are more strongly refracted than paraxial rays. The difference between paraxial and marginal focal lengths is called longitudinal spherical aberration (LSA). It increases with the numerical aperture of the lens. It is difficult to completely suppress and eliminate the spherical aberration even after standard remedial measures, such as polishing, for improving the optical quality of the lens.

In conventional optical systems multiple optical elements are employed to compensate optical aberrations. Upon adjusting the focus position or zoom factor of an optical system, the optical elements have to be translated longitudinally with respect to each other to guarantee optimum imaging quality. This requires a complex design and complex mechanics of optical systems. Adaptive optics with tunable optical aberrations such as asphericity offers the promise of simultaneous small aberrations and simple optical system design.

The easiest approach to assess the optical performance of the adaptive lenses is to measure the shape of the lens and to calculate the resulting refraction properties of the system using ray tracing procedures as implemented in many software packages, such as for instance Zemax. Geometrical properties of captured optical side view images of liquid lenses such as conic constants and eccentricity can be easily extracted and imported to optical simulation platforms like Zemax for evaluating their optical properties. In addition to simple optical imaging of lens shapes, more advanced techniques such as phase-shift interferometry and holography can be used to characterize lens shapes with high accuracy, thereby enabling detailed computations of the resulting optical aberrations. Interferometry is regularly used for measuring optical aberrations present in liquid lenses (see e.g., [25]). Interferometers are often employed for detecting optical aberrations of the lenses. Santiago et al. [25] employed interferometry for computing spherical aberration present in hydro-pneumatically tunable variable focus liquid lens.
2.2c Quantification of Optical Performance

The performance of an optical system is commonly characterized by the modulation transfer function (MTF) and the root mean square (RMS) spot size. The MTF and the spot size are alternative, complementary measures for characterizing the quality of an optical system. The MTF is a numerical measure of the transfer of intensity modulation or contrast from the object to the image. It represents how accurately intensity gradients and details of an object are mapped by an optical system to the image plane. Standard sinusoidal resolution targets are used to measure the MTF in laboratory experiments. They consist of multiple black and white stripes with variable spatial frequencies. Thus, imaging a single target allows us to determine the resolution of an imaging system at a number of spatial frequencies. When an object is imaged through a lens, a higher resolution is obtained for an object with lower spatial frequency. However, as the spatial frequency increases, the contrast degrades, the image is blurred, and the intensity modulation is reduced. While diffraction determines the ultimate limit of modulation transfer, aberrations of non-optimized optical systems frequently lead to a degradation of the image quality for lower spatial frequencies than expected. The closer the MTF of an optical system is to the ideal diffraction limited curve, the better the optical performance of the system [26].

The RMS spot size, on the other hand, describes the distribution of rays on the image plane upon illuminating the full back aperture of the system. The system is diffraction limited if the image spot falls within the confines of the Airy disc. Overall, the MTF provides the more quantitative and complete characterization of the lens properties. Even if all rays in a spot diagram fall within the Airy disc, this is not sufficient to guarantee optimum optical performance, as shown by the deviations in the MTF curves.

In diffraction limited systems, the RMS wavefront error is another valuable measure to quantify deviations from perfect imaging. For optical systems with considerable optical aberrations, the peak to valley (P–V) error can also be of interest. According to the Rayleigh criterion, an optical system is considered optically sound if the P–V error is \( < \lambda/4 \). However, the P–V error only measures the difference between the maximum and minimum values, while the RMS wavefront error illustrates a more holistic picture of the wavefront map by accounting for all crests and troughs. Strehl’s ratio is another standard norm used to analyze optical quality. This ratio is defined as the ratio of the peak intensity of an optical system with aberrations to the diffraction-limited aplanatic optical system without aberrations. A high Strehl’s ratio signifies improved optical performance. This ratio is particularly important for characterizing diffraction-limited systems. Aspherical lenses are in demand because of their superior optical properties: improved aberration control, diffraction-limited MTF, and a higher Strehl’s ratio. Krogmann et al. [27] compared the optical performance of solid fixed-focus microlenses against the tunable liquid lenses. By comparing RMS wavefront error values these authors concluded that liquid microlenses and solid microlenses achieve comparable optical quality.
2.2d Materials and Design Considerations

The functionality and lifetime of optofluidic lenses are often limited by the fabrication material and other design constraints. For instance, membrane-encapsulated lenses suffer from reduced lifetime due to repeated expansion and contraction of the membranes under the application of pressure stimulus. Additionally, unlike pure liquid lenses which have smooth optical surface, membranes require further surface characterization. Similarly, for EW-lenses, Teflon-coated hydrophobic substrates are prone to degradation during regular operation, in particular if water is used as a conductive fluid. Alternative non-aqueous conductive fluids such as ethylene glycol offer much longer lifetimes for EW-lenses. Furthermore, suitable ambient oils as well as the use of AC voltage of sufficiently high frequencies helps to minimize contact angle hysteresis [28].

In addition to the aberrations discussed above, chromatic aberrations also degrade the quality of optical images for conventional color imaging applications. However, specific lens fluids with low dispersion are available that minimize the effect even in the absence of specific corrections. Like for conventional optics, however, it is also possible to compensate for chromatic aberrations beyond material optimization by introducing multi-component lens systems that compensate for each other’s aberrations. Waibel et al. [29] demonstrated such a system composed of different liquids and membranes.

Next to tuning range and aberrations, actuation speed is an important characteristic for adaptive lenses. The maximum speed can depend either on the actuation mechanism or on the intrinsic properties of the deformable lens. Except for the case of thermally driven lenses, which typically involve long thermal relaxation time constants of the entire device, the speed of pressure actuators (e.g., piezos) or electric fields is typically very fast. In this case, the response time of the fluid is usually the limiting factor. A basic estimate of the response time can therefore be obtained by considering the eigenmodes a liquid droplet, determined by the balance of surface tension and inertia. A free droplet in air has a discrete spectrum of eigenmodes with eigenfrequencies given by:

\[ \omega_n = \sqrt{\frac{\gamma}{\rho_i R^3}} \sqrt{n(n-1)(n+2)} \]

as first calculated by Rayleigh in the 19th century. For a millimeter-sized drop of water, this results in an eigenfrequency of approximately 65 Hz for the lowest eigenmode (n = 2). For sessile drops on a solid surface embedded in an ambient oil of finite density and viscosity, these frequencies are slightly reduced. For instance, for the same sized water drop in silicone oil with a viscosity of 5 mPas, the lowest resonance frequency is reduced to 55 Hz [30]. (For higher eigenmodes, the frequency shift is less pronounced.) Exciting the liquid lens at frequencies close to the lowest eigenfrequency generally leads to substantial distortions of the lens surface during actuation, followed by an oscillatory ring-down of the excited eigenmodes. While the addition of viscosity modifiers to the liquid can dampen undesired oscillations following a step-actuation [7], it is generally reasonable to assume that lenses can only be operated up to some critical frequency somewhat below the lowest
eigenfrequency. Actuation frequencies beyond a few tens of Hz can thus only be obtained by reducing the lens aperture to sub-millimeter scales. An exception to this rule is lenses that are operated in an oscillatory mode, in which the focus is continuously modulated between a maximum and a minimum. In this case, actuation frequencies with reasonable optical image quality of up to 3 kHz have been demonstrated experimentally [11,31].

Next, we classify lenses based on their shapes and further sub-classify the lenses according to the respective driving stimulus.

2.3 Spherical Lenses

Liquid spherical drops are ubiquitous in nature. Due to the mismatch in the refractive index between a liquid drop and its ambient fluid, the liquid drop can function as an optical lens. Optical characteristics, such as focal length, of such liquid lenses are determined by the drop configuration and material composition. Thus, by tuning the two parameters, the meniscus curvature and the drop-ambient material phase, one can manipulate the optical properties of liquid lenses. The morphological transition of the liquid–liquid interface can be induced by an umpteen number of driving mechanisms. Other methodologies for fabricating lenses include thermally actuated lenses [13–15], pneumatically driven lenses [32], fluidic pressure lenses [12], membrane-encapsulated fluidic lenses [33], electrochemically activated lenses [34], stimuli-responsive hydrogels [35,36], harmonically driven lenses [31], electrowetting lenses [7–11, etc.]. Such adaptive liquid microlenses have an adjustable focus, and their response time varies from milliseconds to tens of seconds. Based on the actuation mechanism, these microlenses can be further classified into the following types.

2.3a Thermally Driven Lenses

In thermally actuated lenses, the refractive power of an enclosed optical liquid is altered by using thermal expansion. Lee et al. [13] enclosed optical fluid in the conducting ring attached to external heaters. As power is supplied, the induced temperature gradient causes the liquid to expand, consequently increasing its volume and surface area. This, in turn, changes the radius of the curvature and, thus, the focal length.

In a recent study reported by Zhang et al. [14], shown in Figure 2.1A, the surface area of the silicon oil, trapped in the polyacrylate membrane, is increased by increasing the temperature of the ambient air. As the surrounding air expands, it displaces the silicon oil present in the vent connected to a deformable polyacrylate membrane. This causes the enclosed silicon oil to push the flexible membrane radially outward, thus increasing its surface area. The lens shows reasonably good reversible behavior with negligible hysteresis, less than 0.5 mm in focal length, when subjected to heating and cooling cycles. As depicted in Figure 2.1B, the heating and cooling cycle curves overlap as the temperature is increased and decreased, respectively. The voltage requirement for device operation is around 7.5 V. To further quantify the imaging performance, the MTF was measured at different focal lengths, corresponding to different numerical apertures. The best MTF performance was achieved at the longest focal length. The MTF is degraded when the focal
length decreases or the numerical aperture increases. This is contrary to the expected outcome. It occurs because of irregular aspherical deformations as the temperature is raised. Schuhladen et al. [37] employed thermally actuated liquid crystal elastomers to fabricate an Iris-like tunable aperture, mimicking the human eye. Thermally tunable lenses have a serious disadvantage: poor response time, which makes them non-suitable for applications that require fast-switching. Moreover, frequently subjecting the thermally actuated lens device to heating and cooling cycles damages the mechanical structure of the device.

![Fig. 2.1(A) Enclosed silicon oil (light purple) in PMMA membrane is heated by raising the temperature of the ambient air (in yellow). Red contact pads represent the heat source. (B) Back focal length (mm) of the lens vs. temperature during heating and cooling ramps. The solid black line denotes the linear fit of the variation in the power consumption (blue circles) against the increasing temperature. Reprinted by permission from Macmillan Publishers Ltd.: Nature LSA, Zhang et al. [14], copyright 2013.]

### 2.3b Pneumatically Driven Lenses

Liquid lenses are also often constructed with optical liquid enclosed by a membrane. Such lenses are usually operated by applying fluidic pressure or pneumatic actuation or by mechanical stress. Ren et al. [38] demonstrated a mechanically actuated focus tunable liquid lens, by enclosing the liquid under a deformable elastic membrane controlled by a servo motor. Werber and Zappe [39] fabricated tunable microfluidic microlenses activated by fluidic pressure. These membrane-encapsulated fluidic lenses often use PDMS membranes to enclose the lens fluid. PDMS is preferred because of its ease of machinability. Figure 2.2A depicts a pneumatically actuated lens [32]. The optical refractive element is an elastomeric flexible membrane (in dark blue). It is integrated with a mounted camera lens. The diaphragm restricts the amount of light eventually received by the membrane lens. As the vacuum is switched on, the membrane deforms and bends inward, adopting an aspherical configuration. The deformed membrane can act as an optical lens. The dependence of the refractive power of the compound lens system on the applied pressure was further investigated, and the optical system was characterized by imaging black and white strips on a charged couple device (CCD). Such lenses have very short
response times, typically a few milliseconds. However, the lens configuration is not very well defined. Consequently, membrane shapes are not very amenable to standard characterization techniques. External pressure actuators are then employed to change the lens curvature. Piezoelectric, electromagnetic, and thermal actuators have been designed for this purpose.


Choi et al. [40] proposed a magnetically actuated fluidic lens. The optical liquid is entrapped by a double-sided PDMS membrane. Varying the distance between the membrane interfaces can be used to tune the focal length of the doublet lens. In addition, the proposed double-sided lens system compensates for the spherical aberration. Reichelt and Zappe [33] outlined a design for a spherically corrected, achromatic, variable focal length lens. After modeling and optimizing the proposed design on Zemax, the researchers postulated that choosing the appropriate optical liquids of a composite lens system, composed of multiple membrane fabricated lenses, can significantly mitigate chromatic aberration and primary spherical aberration. The lens can be created by pneumatic actuation or by electrowetting. Chronis et al. synthesized a microfluidic network of PDMS-sheathed liquid oil microlenses [41]. The lenses were tuned in tandem in sync by stimulating them pneumatically. Varying the pneumatic pressure can change the focal lengths of the microlenses. Beadie et al. [42] employed compressive mechanical stress to design a composite tunable polymer lens. The lens system consists of a hard PMMA plano convex lens as a backing plate with a PDMS cured plano-convex lens rigidly stacked on the planar surface of the PMMA lens. The researchers observed that the focal length of the composite lens could be changed by a factor of 1.9 mm with applied compression of 1.3 mm. Pneumatic actuation of optical liquids requires membrane encapsulation. This is a disadvantage as it poses an additional demand on membrane characterization; for example, the membrane has to be smooth, with well-controlled RMS roughness. Moreover, membranes are often fragile and are prone to wearing off due to regular usage. This calls for their regular periodical replacement.
A completely different approach was developed by Lopez and Hirsa [31] by fabricating fast-focusing, harmonically driven liquid lenses. Instead of a quasi-static operation, these authors actuated liquid lenses in a dynamic mode by continuously modulating the lens shape at an elevated frequency. The experimental setup shown in Figure 2.2B consists of a 1.82 mm thick Teflon-coated plate, cylindrically drilled along the thickness. The coupled lens system is formed by water droplets pinned on either side of the Teflon plate along the two apertures, each 1.68 mm in diameter. The system is excited by a pressure source at a frequency of 49 Hz. The fast focusing ability of the lens system is confirmed by optically imaging a standard resolution target. Focal length at any given time is calculated with Snell’s law. As the lens optical system is composed of two convex lenses, it has the ability to rectify the spherical aberration. This is due to the fact that aberration due to one lens can be nullified by equivalent aberration of opposite magnitude by the other lens. However, since the lens is operated in ambient air rather than in another liquid, it remains vulnerable to evaporation. Hence, the lens meniscus cannot sustain its initial topography and suffers from poor shelf life. Due to the absence of any ambient liquid, the effect of gravity, which induces flatness in the lens profiles, cannot be neglected.

2.3c Stimuli-Responsive Lenses

![Fig. 2.3(a) Experimental setup; (b) liquid meniscus in a circular aperture via the pinned contact line formed by the top hydrophobic surface, represented by ts and hydrophilic bottom substrate and sidewalls. The contact angles ca are modulated by an entrapped stimuli-responsive hydrogel. Dashed blue lines represent a divergent lens while red dashed lines correspond to the convergent lens profile. (c–f) Morphology of the water–oil interface at different temperatures. Reprinted by permission from Macmillan Publishers Ltd.: Nature, Dong et al. [35], copyright 2006.](image)

Stimuli-responsive hydrogels can also be employed as a viable tool for manipulating the curvature of the water–oil interface to produce variable focal length microlenses. In the
system described by Dong et al. [35], shown in Figure 3, a hydrogel ring is sandwiched between the two plates; the top plate has an opening. The microfluidic channel, shown in Figure 2.3, is filled with water. The hydrogel ring is surrounded by a polymer jacket to constrain the expansion or contraction of the hydrogel. Water is then loaded into the space, enclosing the hydrogel ring and the plates, followed by oil as an ambient fluid. The hydrogel expands or shrinks in response to the external stimulus, thus changing the volume of the enclosed water, which alters the curvature of the oil–water interface from flat to some arbitrary spherical shape that corresponds to a specific Laplace pressure. The contact line is firmly pinned by the hydrophobic–hydrophilic aperture boundary. The change in the curvature of the interface, which can be translated into respective focal lengths, depends on the strength of the stimulus. The external stimuli can be temperature or pH. The liquid meniscus grows at a lower temperature. This is because the volume of water lost due to absorption by the hydrogel is less than the expanded volume of the hydrogel itself. Conversely, at higher temperatures, the meniscus shrinks as the amount of water expelled is considerably less than the contracted volume of the hydrogel ring. However, these lenses suffer from a long response time, typically 12–15 s. In addition, the spherical shape of the droplet is retained, leaving such lenses vulnerable to optical aberrations. Zeng et al. [43] improved the response time by using infrared actuation of a light-responsive hydrogel. For a broader field of view, Zhu et al. [36] fabricated a microlens array on a curved hemispherical glass surface. A thermo-responsive hydrogel was employed to regulate the curvature of the water–silicone oil meniscus. The curvilinear configuration has a significant advantage over the planar surface by offering a much larger field of view.

Miccio et al. [44] experimentally demonstrated the potential application of RBCs as a tunable liquid bio-lens. The focal length can be tuned by altering the osmolarity of the ambient medium. Imaging through the RBCs array helps in diagnosing the blood deficiencies. This was ascertained by dynamic wavefront characterization the RBCs lens array, further corroborated by numerical modelling. Any blood disorder can be readily identified by the deviation of focal spots as observed through the RBCs of diseased blood samples compared to normal healthy cases. However, the development of such bio-lenses is still in its infancy and requires more attention. The lenses suffer from a long response time of typically 10 s because of a delay between the variation of the osmolarity of the ambient medium and the response of the lens.

2.3.3 Electrically Driven Lenses

Liquid manipulation by electric field [45,46] is also widely investigated because of its paramount importance in domains such as adaptive optics, optical switching, displays, etc. EW lenses [7–11] are fast, demonstrating excellent switching speed, and offer a good degree of tunability in focal length. They offer higher flexibility in design without any mechanically moving parts. The concept has also been explored for miniaturized systems. However, in most of the studies reported so far, the spherical shape of the lens meniscus is restored, and thus these lenses suffer from spherical aberrations, which, in turn, decrease
their optical performance. EW [47] modulates the contact angles between the fluid and the substrate on which the liquid drop rests. The general EW equation is:

\[
\cos \theta = \cos \theta_0 + \frac{\varepsilon \varepsilon_0}{2d \gamma} U^2
\]

where \( \theta_0 \) is the Young angle at zero voltage, \( \theta \) is the contact angle under the influence of applied voltage \( U \), \( d \) is the thickness of the dielectric, \( \gamma \) is the liquid–liquid interfacial tension, \( \varepsilon \) is the electrical permittivity of the droplet fluid, and \( \varepsilon_0 \) is the permittivity of the free space. Thus, applying a potential \( U \) between the droplet and the dielectric can alter the contact angle between the drop and the substrate on which the droplet rests. One challenge is that the droplet should remain at its optical center, thus precluding any unwanted optical distortions. This has been successfully achieved by adopting various self-centered lens designs. In the system reported by Kuiper and Hendriks [8], depicted in Figure 2.4, the liquid–liquid interface is modulated by EW actuation on the sidewalls. The sidewall consists of embedded electrodes coated with a hydrophobic dielectric layer, capable of electrowetting modulation. The entire system is integrated in a cylindrical housing. Conducting aqueous solution is used in the drop phase, while insulating fluid is employed as an ambient liquid. The presence of ambient fluid also arrests the evaporation of the drop fluid. Due to the density-matched system, the Bond number is sufficiently low, and consequently the meniscus shape is not measurably affected by the gravitational forces. As the voltage is applied, the interface adopts convex and concave shapes in a tunable fashion and attains a flat interface intermittently. This is shown in Figure 2.4. The effect of fluid viscosities on the switching speed of the lenses was also investigated. Optimized performance is obtained for critically damped systems, e.g., by adding suitable viscosity modifiers such as PEO (polyethylene oxide) [7,8]. These lens systems are devoid of meniscus oscillations and hence focusing speed is not sacrificed.

In the pioneering work by Berge et al. [7], EW lenses were manufactured with wettability gradients. The gradient is induced by using dielectrics of variable thicknesses. In addition, the focal distance of such a lens can be tuned in a reversible manner as voltage is applied and released back and forth. The first plot of Figure 2.5A shows the variation in power (in diopters) for the applied voltage of a 6 mm diameter lens, filled with \( \alpha \)-chlonaphthalene as the insulating fluid and the aqueous solution of sodium sulfate as the ambient fluid. Superimposition of the two curves, corresponding to forward and backward cycles, respectively, clearly depicts the very reversible nature of the liquid lens. Electrowetting was further explored by Krogman et al. [48], employing trapezoidal grooves as sidewalls for EW. The technique was particularly successful in self-centering the liquid lens along its optical axis. Figure 2.5B depicts the variation in the focal length against the applied electrowetting voltage. They applied voltage to tune the focal length from 2.3 mm at 0 V to a flat interface with infinite focal length at 45 V. Lee et al. [49] carried out numerical simulations and studied the evolving meniscus shapes with an application of EW,
**Fig. 2.4**(a) Liquid lens system in a cylindrical housing. The red surface denotes conducting electrodes, followed by insulator coating (in green) with further deposition of hydrophobic coating. Conducting fluid (dark blue) forms a convergent lens at zero voltage. **(b)** Application of voltage 'V' modulates the meniscus shape to a convergent lens profile. **(c–e)** Topological change in lens shape from initially divergent spherical meniscus at zero voltage to a flat interface at 100 V and subsequently to convergent lens at 120 V. Reprinted from Kuiper, S.; Hendriks, B.H.W. Variable-focus liquid lens for miniature cameras. Appl. Phys. Lett. 2004, 85, 1128–1130. With the permission of AIP Publishing.

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**Fig. 2.5**(A) Variation in focal length (in mm) and power of lens (inverse of focal length) with the applied voltage. The two curves superimpose as the voltage is increased and decreased, respectively. With kind permission of the European Physical Journal E (EPJE). Adapted from Berge, B.; Peseux, J. Variable focal lens controlled by an external voltage: An application of electrowetting. Eur. Phys. J. E 2000, 3, 159–163. **(B)** Measured and theoretical values of back focal length (in μm) vs. applied electrowetting voltage (in volts). With kind permission of The IOP Publishing material. Adapted from Krogmann, F.; Monch, W.; Zappe, H. A MEMS-based variable micro-lens system. J. Opt. A Pure Appl. Opt. 2006, 8, S330–S336.
corroborating the experimental findings of Krogman et al. [48]. They also showed that spherical aberration can be essentially eliminated by applying an electric field on the spherical liquid meniscus entrapped in the groove. Characterization of the dynamic mechanical stability of liquid-filled lenses was also studied by Yu et al. [50].

The concept of creating a single EW-modulated microlens can be further extended to create a microlens array. The methodology was demonstrated by Murade et al. [11], as shown in Figure 2.6. The experiment consisted of two plates with an aperture in the top plate and a bottom plate capable of electrowetting modulation. By using the pinned contact lines, the water droplet is entrapped in the aperture and is sandwiched between the two plates. Pressure in the droplet is regulated by applying the voltage between the two plates. Hysteresis on the bottom plate is reduced by soaking it in the silicone oil. The reduced hysteresis causes frictionless movement of the contact line on the bottom plate. Hysteresis can be further suppressed by employing high AC frequency [28] for efficient depinning of the contact lines. This essentially prevents the contact line of the droplet being trapped in the defects. As the voltage is applied, the contact angle on the bottom substrate decreases, consequently lowering the pressure in the entrapped droplet. This leads to an increased radius of curvature and, thus, enhanced focal length. Parallelization into the microlens array is realized by integrating multiple apertures. This approach requires a single actuation electrode and, thus, precludes the use of a dedicated addressable electrode for each individual spherical lens. The focal length of all microlenses can be tuned simultaneously by regulating the pressure in a single reservoir droplet. The optical performance of the device is demonstrated by synchronous modulation of focal lengths beyond 1 kHz. The device has additional applications in integral imaging and 3D imaging. Replacing the conductive lens fluid with a dielectric fluid results in a dielectric lens system [51–53]. Due to the non-zero electric field across the dielectric lens fluid, it experiences additional bulk force due to the gradient in the electric field.

Grilli et al. [54] fabricated a microlens array using polar electric crystal of LiNbO₃. This was achieved by depositing a thin oil film on square array of hexagonal LiNbO₃ crystals. The periodically poled crystal substrates are electrically actuated by the pyro-electric effect, by subjecting the crystals to subsequent heating and cooling cycles, altering the oil topography and consequently modifying the surface tension, thereby producing a microlens array. The focal length is measured from the phase profiles extracted by interferometric measurements. The configuration is electrode-less, does not require any external electrical circuits, and is devoid of any mechanically moving parts. A similar electrode-less arrangement was utilized by Miccio et al. [55] for constructing tunable liquid micro-lens array. The pyro-electric activation of polar dielectric crystals generated two different regimes: separated lens regime (SLR) and wave-like lens regime (WLR). The lens aberrations were computed by analyzing the wavefront maps.

Gorman et al. [56] demonstrated the principle of controlling the lens shape with electrochemical desorption. The surface properties of the gold surface are manipulated by applying potential across the self-assembled monolayers. Focal length can also be tuned by electrochemically modulating the surface tension of the lens liquid [34]. The
Electrochemical activation is attained by applying the voltage across the lens medium. Lee et al. [57] propounded the construction of variable focus, tunable liquid lens using a deformable PDMS membrane. Electromagnetic stimulation was used to apply pressure on the membrane, thus changing the focal length of the lens. Electroactive polymers (EAPs) are also promising candidates because of their low response time and high flexibility. Choi et al. [58] exploited the EAP actuation to generate fluidic pressure that can be directed to modulate the shape of a transparent elastomer membrane. By modulating the strength of EAP actuation, varying degrees of change in the focal length of the lens membrane can be produced.

**Fig. 2.6(a)** Schematic representation of a microlens array. The PCF logo imaged from the top. **(b)** Array of PCF images formed by individual microlenses. **(c)** Side view of the microlens array. Application of voltage $U$ modulates the contact angle of the sandwiched liquid on the bottom substrate, consequently altering the lens angle $\alpha$, which in turn changes the curvature and the focal length of the pinned droplet. With kind permission of the Optical Society of America (OSA). Adapted from Murade, C.U.; van der Ende, D.; Mugele, F. High speed adaptive liquid microlens array. Opt. Express 2012, 20, 18180–18187.

Liquid lens technology also involves designing lithographically structured electrodes to constrain droplet movement. In a study reported by Kruipenkin et al. [9], the droplet position can be altered by applying bias voltage across specific electrodes. It can also be constrained at the center by applying equal voltage on the electrode. These electrodes induce a spatially heterogeneous electric field, thus intensifying the field strength at specified locations and in a particular direction, eventually driving the material flow along the intensified field path. Liu et al. [10] employed double-ring planar electrodes for fabricating electrowetting actuated liquid lenses. Xu et al. [59] designed a dielectrically actuated lens placed on a well-shaped bottom electrode with a top planar electrode. This arrangement provides automatic self-centering of the dielectric liquid droplet trapped in the well-shaped electrode.
2.4 Non-Spherical Lenses

Non-spherical lenses can be broadly categorized into two types: aspherical lenses and cylindrical lenses. Unlike spherical lenses that have a fixed unique curvature, these lenses have a variable curvature along the surface profile. Out of all possible aberrations, spherical aberration is the most difficult to eliminate. Due to the varying curvature, aspherical lenses can overcome spherical aberration. Moreover, liquid aspherical lenses are also tunable in focal length, apart from correcting spherical aberration. They can be used to replace multiple spherical lenses in any specific optical system, thus reducing the complexity and weight of the overall optical equipment. Another class of non-spherical lenses is called astigmatic or cylindrical lenses. Astigmatism occurs because of rotational asymmetry between two principal axes perpendicular to each other, namely, tangential and meridional. Thus, such an optical surface has multiple foci. The degree of astigmatism depends on the separation between the two focal points. Spherical lenses, which are rotationally symmetric, have a single radius of curvature and thus do not exhibit astigmatic properties, as any beam of light impinged on a spherical lens will converge or appear to converge to the same focal point. However, subjecting elastomeric or fluidic lenses to asymmetric strain imparts asymmetry in the rotational configuration. Consequently, the curvature of the lens along the two axes, tangential and meridional, is different. Thus, instead of a single focus, the strained astigmatic lens possesses two astigmatic foci. This strain can be induced by a number of other mechanisms. Imaging a point through cylindrical lens yields a line. This is further illustrated by the MTF plots of the spherical and astigmatic lenses depicted in Figure 2.7.

Fig. 2.7(A) Experimentally measured MTF curves of tunable liquid lenses under increasing pneumatic pressure from 1 to 10 kPa. With kind permission of the Optical Society of America (OSA). Adapted from Zhang, W.; Aljasem, K.; Zappe, H.; Seifert, A. Highly flexible mtf measurement system for tunable micro lenses. Opt Express 2010, 18, 12458–12469. (B) The MTF of the astigmatic lens along two axes: tangential (T) and sagittal (S) vs. frequency. The black curve signifies the diffraction-limited MTF. With kind permission of the Optical Society of America (OSA). Adapted from Lima, N.C.; Cavalli, A.; Mishra, K.; Mugele, F. Numerical simulation of astigmatic liquid lenses tuned by a stripe electrode. Opt. Express 2016, 24, 4210–4220.
Zhang et al. [60] devised an experimental technique to measure the MTF of a PDMS-enclosed liquid lens at different pneumatic pressures. As shown in Figure 2.7A, as the applied pressure is increased from 1 to 10 kPa, the MTF degrades. This can be attributed to the increase in optical aberrations at higher pressures. Similarly, in the study of astigmatic lenses reported by Lima et al. [61], astigmatism becomes more pronounced, as the voltage is applied between the liquid meniscus and the stripe electrode. The two blue curves, shown in Figure 2.7B, represent the MTFs along two axes, tangential (T) and sagittal (S), while the black curve represents the diffraction-limited MTF. The higher the divergence between the two curves (T and S), the larger the degree of astigmatism present in any optical system.

In subsequent sections, we shall explore the various driving mechanisms for achieving the requisite asphericity and astigmatism. Next, we classify non-spherical lenses based on their driving mechanism.

2.4a Electrically Driven Aspherical and Cylindrical Lenses

Oh et al. [62] showed that the electric field is a potent tool for effectively switching a liquid micro-meniscus pinned by a circular aperture. As the potential is applied between the conducting droplet and the bottom electrode, kept at distance $h$ from the aperture plate, the droplet is transformed into different aspherical shapes and assumes morphologies ranging from a parabola to a hyperbola and then to higher degrees of aspherical configurations. These shapes can be characterized by profile extraction techniques followed by fitting protocols, from which the nature of the conic section can be inferred. The meniscus acquires aspherical shapes of varying eccentricities as the voltage increases from 0 to 1700 V, starting from an initially flat interface. The switchability behavior depends on the aspect ratio of the pillars. The equilibrium surface profiles are calculated by balancing the electrical Maxwell stress and the Laplace pressure determined by:

$$\Delta P_b = 2\gamma \kappa(r) - \Pi_{el}(r) \tag{2.7}$$

where $\Pi_{el}(r) = \varepsilon \varepsilon_0 E(r)^2$ is the electric Maxwell stress. ($\varepsilon_0$: dielectric permittivity of the oil). Considerable effort has been expended to fabricate aspherical polymeric lenses with the application of an electric field. Zhan et al. [63] fabricated polymeric aspherical lenses by applying an electric field to a droplet of SU-8 25 resting on a planar electrode surface. Under finite voltage, the polymeric material experiences Maxwell stress and acquires an aspherical shape. The materials are then subjected to UV curing for solidification. The captured droplet image profiles are fitted with the standard aspherical lens equation. The conic constant and the curvature of the droplet at the apex are extracted from the fitted profile. Droplet morphology is distorted by the application of voltage from an initially spherical shape at zero voltage to higher degree conics at a finite voltage. Beyond a critical voltage of 5150 V, the electrostatic force exceeds the restoring Laplace pressure, and the droplet becomes unstable. The spatial resolution of the cured aspherical lens, as given by the Rayleigh criterion, is 1.325 μm, which is smaller than the diameter of the airy disc. The sagittal and tangential MTF curves approach the diffraction-limited MTF. Further, the lens has a Strehl’s ratio of 0.742. The calculated optical metrics indicate that the lens has
significantly reduced aberrations. However, these lenses are not tunable. During fabrication, the polymer responds slowly to the applied electric field to assume the desired shape. Once cured with UV light, however, the shape and thus the optical properties of the lenses are fixed like for any ordinary solid lens. Polymeric lenses require further characterization of surface smoothness. Kuo et al. [64] fabricated a tunable SU-8 negative photosensitive aspherical microlens array by electrostatically pulling the SU-8 microdrops. The aspherical drops are further UV cured. The asphericity of the conical shapes is controlled by the applied voltage.

However, truly adaptive optics requires working with liquid lenses so that the focal length can be tuned back and forth by the application and release of driving pressure. Mishra et al. [65] therefore recently exploited insights from recent numerical simulations ([62]), to experimentally demonstrate an optofluidic lens with tunable focal length and asphericity. The researchers showed that two control parameters, the electric field and the hydrostatic pressure, can be used to tune the asphericity and focal length independently. The device is illustrated in Figure 2.8A. Simultaneously varying the hydrostatic pressure and voltage achieves a hyperbolic lens profile of the liquid–liquid interface with reduced longitudinal spherical aberration (LSA). Silicone oil is used as an insulating ambient fluid while aqueous salt solution is used in the droplet phase. The refractive index ratio was 1.10. Because of the density-matched system, the bond number is low, and thus, the effect of gravity can be neglected. Conducting experiments in fluidic ambience also arrests evaporation. Droplet interface profiles extracted experimentally are confirmed with electro-fluidic simulations using COMSOL Multiphysics. Further, they successfully demonstrated the concept by imaging a square grid. Not only is the LSA mitigated but also, in the process, distortion is suppressed, restoring the flat topography of the original grid (Figure 2.8B). The voltage required ranged from several hundred volts up to more than 1 kV. However, the voltage can be reduced by optimizing the device configuration with more rigorous numerical analysis. This includes choosing liquids with lower interfacial tension, enlarging the aperture size, and reducing the spacing between the aperture plate and the top electrode.

The same concept can also be extended to arbitrarily shaped electrodes that replace the flat plate electrode above the lens. Lima et al. [61] recently characterized the optical performance of an astigmatic lens by studying the variation in the corresponding Zernike coefficient on Zemax. The astigmatic lens is created by subjecting the liquid meniscus to an electric field using a stripe electrode. It was shown that the maximum tuning range of astigmatism is achieved when the stripe width of the electrode is half of the aperture diameter. Cylindrical liquid crystal lenses [66] are fabricated by applying a spatially non-uniform electric field on the homogenous liquid crystal. This is achieved by using a stripe ITO electrode as the top substrate with liquid crystal resting on the planar bottom substrate. Applying voltage deforms the lens along the stripe, thus creating a directional strain. Miccio et al. [67] exploited the concept of pyro-electrowetting for fabricating hemicylindrical and toroidal liquid lenses, followed by their interferometric characterization.
Electrically driven aspherical lenses come with a significant advantage over regular spherical lenses. Such lenses are not only tunable in their focal length, but can also be tuned independently for correcting optical aberrations. Thus, their inclusion can improve the overall performance of the optical system.

![Fig. 2.8](image)

**Fig. 2.8(A)** Schematic of the aspherical lens device with a photograph of the actual device in the inset. Aqueous cesium iodide solution as lens fluid (in blue) with silicone oil as ambient liquid (in yellow). The curvature of the spherical meniscus (in red) at zero voltage is controlled by the hydrostatic head (in black). Application of voltage ‘U’ between the top electrode and the aperture plate (both in orange) distorts the shape of the spherical droplet, thus making a perfect aspherical lens. **(B)** The spherical (red) and aspherical droplet profiles (green) with captured images of the square grid demonstrate the mitigation of longitudinal spherical aberration (LSA). Reprinted by permission from Macmillan Publishers Ltd.: Scientific Reports, Mishra et al. [65], copyright 2013.

### 2.4b Thermally Driven Lenses

Lee et al. [68] fabricated PDMS microlenses with tunable astigmatism by exploiting the anisotropic joule heating produced by passing current through an elliptical silicon ring enclosed at the center of the PDMS lens. The applied current deforms the polymeric material asymmetrically. The lens can be tuned reversibly by turning the heat on and off. The astigmatic focal distance can be changed from 1590 to 44 μm by increasing the input current from 0 to 30 mA. Subjecting the lens polymeric material to heating and cooling cycles deteriorates the lens fabric.

### 2.4c Mechanically Driven Lenses

Liebetraut et al. [18] (Figure 2.9) demonstrated that applying the azimuthal asymmetric strain in a controlled manner on an elastomeric PDMS lens can reversibly switch the astigmatism on and off, simultaneously tuning the focal length. The lens can be astigmatically tuned by anisotropic actuation, by applying radial pressure along the four independent axis. This is a significant improvement over previously reported approaches [68], in which a deformable soft polymer is used to modulate the focal length under the applied stimuli. In these cases, the actuation was unidirectional and was possible only along one axis. However, the current approach of mechanical strain offers actuation possibilities
along multiple directions. Figure 2.9A shows the schematic of the rigidly anchored PDMS lens attached with eight actuators, each controlled by a servo motor. The unstrained initial focal length of the PDMS lens is 32.6 mm. The lenses were optically characterized by an SHWS by studying the wavefront errors of first 36 Zernike coefficients. Astigmatism can be tuned over a range of 3 μm and focal length over +2.3 mm.

![Schematic of elastomeric polymer anchored lens](image)

**Fig. 2.9(A)** (a) Schematic of elastomeric polymer anchored lens; (b) one of the actuation axes (in red dashed lines). $F_{eq}$ denotes the applied radial force required to change the curvature of the lens while $F_{el}$ represents the restoring force due to polymeric lens material. (c) Labeling of the four actuation axis. (B) Picture of the anchored lens with servo motors. Reprinted by permission from Macmillan Publishers Ltd.: Nature LSA, Liebetraut et al. [18], copyright 2013.

### 2.4d Hydrodynamically Driven Lenses

Yu et al. [69] designed a PDMS-encapsulated, adaptive liquid lens with one aspherical surface. The other surface, which is spherical, is modulated by fluidic pressure. Simulations conducted on Zemax show that the lens configuration significantly reduces the spherical aberration more than plano-convex lenses. The optimized spherical aberration was found to be $-0.000059$ waves compared to 2.03 waves for spherical lenses at optimized focus. The corresponding P-V and RMS of the wavefront error were also substantially reduced. Zhao et al. [70] devised a procedure for developing an endoscopic microscope by combining two liquid tunable aspherical lenses along with conventional customized plano-convex lenses. Tunability precludes any type of longitudinal translation between individual lens elements. The inter-element distance is optimized by the optical simulation platform Zemax. Moreover, the combined lens system acts as a potential zoom lens, offering a much larger field of view (FOV) and simultaneously ensuring high optical resolution. This fosters the imaging potential in endoscopic operations, as one needs to discern fine details with sufficient zoom while simultaneously capturing a large area for visualization. The performance of the composite optical system is quantified by measuring the MTF. For optimized aspherical lens parameters, the MTF of a system approaches the diffraction-limited MTF curve. However, pertinent literature and scientific investigations in devising such aspherical lens systems are still scarce. Mao et al. [71] designed and fabricated hydrodynamically tunable optofluidic cylindrical microlens by utilizing the interface between the laminar streams of 5 M calcium chloride and deionized water with a refractive index
The interface experiences centrifugal force as the streams pass through the curved trajectory. Optimal calibration of the flow rates of the streams can be used to tune the focal length of the interfacial cylindrical lens. Higher flow rates result in shorter focal lengths. Zhao et al. [72] constructed a cylindrical microlens array by manually translating the piston, which, in turn, pushes the fluid, creating the liquid lens array in drilled apertures. This offers a higher dynamic range and is capable of characterizing a highly aberrated wavefront. Marks et al. [73] constructed an adaptive fluidic phoropter consisting of astigmatic and defocus lenses, designed for ophthalmic applications. The phoropter offers advantages over the conventional customized phoropter by decreasing the eye inspection time and being more compact and handy because of the considerably reduced size.

2.5 Outlook: Advanced optofluidic imaging systems for the future

The quality of optical images is frequently limited by the aberrations introduced either by the imaging optics or by the sample of interest, as for instance in microscopy applications. The primary benefit of micro-optical systems is their compactness. Unlike macroscopic optical systems, it is usually not possible to introduce additional optical elements to compensate aberrations without sacrificing this primary benefit of the approach. Adaptive micro-optics with aberration control offers a great opportunity to overcome this bottleneck and develop high-quality imaging optics for confined spaces with flexible aberration control. The recent examples sketched in the preceding sections should be considered as a first indication of the potential that these techniques can offer. Elastomeric lenses such as the one described in [18] already provide a great degree of flexibility and control over a variety of independent types of aberrations. Challenges for device development and true micro-optical integration of such devices include stability of the materials over (hundreds) of thousands of actuation cycles and the miniaturization of the external mechanical actuators. The electrically actuated lenses with aberration control seem to be more flexible in that respect. Miniaturization is not an issue because the actuation only requires patterned electrodes with dimensions of tens of micrometers that are easy to fabricate and connect. Long-term stability of the material is an issue, yet extensive developments in the context of commercially available EW-adaptive lenses (e.g., by Parrot/Varioptic Inc.) and display technology (e.g., Amazon/Liquavista) demonstrate the existence of reliable solutions to these problems. A technical concern, however, may arise from the rather high voltages of several hundred volts that had to be used in the first demonstrators [65]. Many applications will probably benefit optimized designs with reduced voltages.

Notwithstanding the practical challenge of high voltages, the degree of flexibility offered by electrically actuated lenses is tremendous. It is easy to extend the concepts of [65] to arbitrary electrode geometries that enable flexible control of a large spectrum of aberrations. The numerical study by Lima et al. [61] demonstrates this for a simple stripe electrode that introduces astigmatism. Yet, by making use of arrays of electrodes and even wider degree of flexibility can be achieved. Designs with, say, $10 \times 10$ or $100 \times 100$ individually addressable electrodes are easy to design and manufacture. Thanks to the quantitative numerical models that are available, systems can be designed to match the
needs. Given the arbitrary number of actuators, such devices may eventually offer an even higher degree of flexibility than elastomeric devices. For instance, it is anticipated that the combination of pressure control and individually addressable segmented electrodes will enable the creation of lenses with surface profiles that vary between regions with positive and negative curvature within the same lens to generate almost arbitrary shapes of focal spots. In combination with suitable online wavefront metrology and self-learning algorithms, such devices could provide hitherto unimaginable flexibility of wavefront control.

One important challenge to introducing liquid lenses into a broader range of application fields would be the scaling up of their dimensions. For standard microscopy applications (including confocal), apertures of several (>5 mm) millimeters would be highly desirable. Control of gravitational and other distortions by suitable electric fields applied to segmented electrodes may offer a route to overcome such challenges in future devices.

The strength of such adaptive micro-lenses can be further enhanced by integrating them with other adaptive micro- and optofluidics devices for light manipulation that have been developed in recent years in parallel with the advances in optofluidics lenses discussed in this work. Figure 2.10 illustrates a few examples of such devices that can be integrated into various optical devices for a wide range of applications, from photonics [74], display technologies [75], and the biomedical industry to integral imaging for 3D vision [76]. These examples include elements such as shutters [77], beam steering prisms [78], and controllable reflectors [79]. All examples shown make use of the enormous flexibility of electrowetting to manipulate the shape and orientation of fluid interfaces.

Figure 2.10A shows a shutter of a variable circular aperture that can be tuned between 0.2 and 1.2 mm in diameter on a time scale of a 2 ms for the opening and of approximately 100 ms for switching off. This strong asymmetry is governed by the fact that the switching-off process in this device is driven by capillary forces only. i.e., it is not supported by EW. Figure 2.10B shows an EW-actuated microprism with a flat (uncurved) liquid–liquid interface of variable tilt [78] that enables steering of beams in two independent directions on a time scale of ms. Similarly, wedge-shaped geometric structures can be exploited to create efficient switchable retroreflectors [79] by alternating between a flat and a curved liquid–liquid interface, Figure 2.10C. Recently, Schuhladen et al. [80] constructed a tunable optofluidic slit aperture actuated by AC electrowetting.

Other future developments may arise in the area of integral imaging for 3D vision. While tunable optofluidic microlens arrays have been demonstrated, their application to enhance the accessible focal depth of 3D imaging systems has yet to be explored. If combined with aberration control, as discussed above, such devices might lead to breakthroughs in quantitative 3D metrology, e.g., in industrial applications such as quality control.
Fig. 2.10 (A) (a) Incident light beam is absorbed by the “Oil + dye” medium; (b) application of voltage “U” exerts electrical Maxwell stress on the water-oil meniscus, enabling the incoming light to pass through the “Oil + dye” medium. With kind permission of the Optical Society of America (OSA). Adapted from Murade, C.U.; Oh, J.M.; van den Ende, D.; Mugele, F. Electrowetting driven optical switch and tunable aperture. Opt. Express 2011, 19, 15525–15531. (B) Schematic of the electrowetting modulated microprisms. (a) Conducting liquid entrapped between the silicon walls coated with fluoropolymer; (b) side view of the setup at zero voltage; (c) application of voltage, with 30 V (left sidewall) and 80 V (right sidewall), entrapped conducting liquid electrowets the sidewalls, thus forming a triangular prism; (d) inset of the contact line at the edge. With kind permission of the Optical Society of America (OSA). Adapted from Smith, N.R.; Abeysinghe, D.C.; Haus, J.W.; Heikenfeld, J. Agile wide-angle beam steering with electrowetting microprisms. Opt. Express 2006, 14, 6557–6563. (C) Schematic of the retroreflector. (a) Concave interface is formed between the low index water and high index oil at zero voltage, exhibiting scattering or semi-diffused reflection. Inset depicting the contact angle $\theta_Y$ between water, oil, and hydrophobic dielectric deposited on reflective electrode. (b) Transition from concave to flat interface at 19 V showing retroreflection. With kind permission of the Optical Society of America (OSA). Adapted from Kilaru, M.K.; Yang, J.; Heikenfeld, J. Advanced characterization of electrowetting retroreflectors. Opt. Express 2009, 17, 17563–17569.
2.6 Conclusions

The review summarized the classification of optofluidic lenses based on their shapes and driving mechanisms and briefly sketched the standard tools employed for their characterization. The main focus is on two aspects of lens performance: tunability of the focal length and the more recent developments on aberration control. Liquid spherical lenses, although tunable in the focal length, are inherently compromised by optical aberrations. Thus, these lenses do not improve the optical quality of the captured image. Further, solid aspherical lenses are expensive and require high mechanical precision in their fabrication. Moreover, they are designed for a single focal point. Tunable aspherical lenses, with a reversibly tunable focal length, are promising candidates for suppressing spherical aberration and for improving optical resolution. Liquid lenses can also be a substitute for GRIN lenses. By choosing suitable fluid compositions and controlling their dispersion, one can minimize chromatic aberrations. We also discussed various lens tuning mechanisms. Each mechanism has a distinct operational procedure and has its own set of advantages and disadvantages; for example, actuation mechanisms involving microfluidic vents for directing liquids have a long response time. This may be due to the high fluidic resistance encountered in microfluidic systems. Similarly, for thermally actuated lenses, there is a considerable delay between the heating and cooling cycles, due to the low coefficient of thermal expansion, and thus, there is a lag in response. However, these approaches offer better control over lens morphology by carefully regulating the temperature, for thermally actuated lenses, or the fluid pressure, for hydrodynamically manipulated lenses. Electric fields offer a more detailed and faster control. Companies such as Liquivista and Varioptic/Parrot manufacture reliable electrowetting devices that have a long shelf life, demonstrate excellent performance over continuous operation, and last for multiple actuation cycles. The application of an electric field also provides an inexpensive approach for designing tunable liquid aspherical lenses with a minimum of mechanical actuators. Electrically actuated liquid lenses enable the scanning of objects at varying distances and simultaneously compensate for spherical aberrations. Despite the technological flexibility that has been demonstrated for a few examples, aberration control still requires rather high voltages, typically several hundreds of volts. Overall, the development of devices with aberration control—be it with electrical actuation or with elastomeric lenses—is still in its infancy and deserves more attention and optimization. Improving robustness and fabrication procedures as well as the long-term stability of the devices are additional aspects that need to be addressed.

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References


Chapter 3

Tools and Methods

Abstract
In the ensuing chapter, we will study the various methods employed for characterization of lenses. This will include discerning the optimum lens shapes for improved imaging and introduction to standard optical parameters for assessing the performance of any optical system. The optical metrics determining the image quality such as Modulation transfer function (MTF), Strehl’s ratio and Root mean square (RMS) spot size are discussed in detail. Next, we shall investigate two fundamental properties of conic lenses: focal length and longitudinal spherical aberration (LSA) by employing geometrical ray tracing. Following this, we shall discuss the concept of optical imaging and aberrations. It comprises a brief introduction to the wavefront aberrations, followed by the mathematical foundation of its representation by Zernike polynomials. We shall elucidate the significance of Zernike coefficients and their impact on the respective aberrations. Finally, we will conclude by discussing the operation of optical simulation tool Zemax, which we will employ in forthcoming chapters to characterize our optofluidic lenses.
3.1 Geometrical analysis of conic lenses

Consider an aspherical lens profile as shown in the figure 3.1. The ray of light (Fig. 3.1) undergoes refraction at the lens interface whenever it encounters a discontinuity in the refractive indices of the two mediums, obeying Snell’s law. Spherical aberration occurs because of the inability of a lens to converge all the impinging rays to a single focal point. This is due to the variation in degree of refraction along the lens surface. Marginal rays (shown in dark green in Fig. 3.1) that strike the aspherical surface (shown in red in Fig. 3.1) above the critical angle of refraction, undergo total internal reflection and hence, are unrefracted. We define “impact distance” as the distance of the striking optical ray from the optical axis. “Critical impact distance” is defined as the distance beyond which all the rays impinging on the lens undergo total internal reflection and are unrefracted. LSA (PM) is the difference between the paraxial focus (P) and marginal focus (M) as measured from the optical center (O). For a perfect lens, LSA is zero. The higher the refractive index ratio of the lens medium to the ambient medium, the higher is the refractive power of the lens. In order to compute the pertinent focal lengths and LSAs, we assume that the lens has a conic profile, with all aspherical coefficients in equation 2.4. being zero.

Fig. 3.1. Schematic of an aspherical planoconvex lens (red). An optical ray (dark green), parallel to the optical axis (dotted black), called marginal ray falls on the lens, is refracted and hits the optical axis at M. Another ray (light blue), parallel and close to the optical axis, called paraxial ray, hits optical axis at paraxial focal point P. PM denotes the LSA and \( n_1 > n_2 \). h signifies lens deflection from the horizontal axis (dotted navy blue).

In fig. 3.1, LSA is positive as the paraxial focus lies ahead of the marginal focus along the principal axis. Notationally, LSA is defined as
\[ LSA = f_p - f_m \quad \ldots 3.1 \]

where, \( f_p \) (OP in fig. 3.1.) is the paraxial focal length and \( f_m \) (OM in fig. 3.1.) is the marginal focal length. \( f_p = OP \) and \( f_m = OM \). \( N \) is the local normal to the lens interface.

The critical angle of refraction, \( \theta_c \), beyond which all marginal rays undergo total internal reflection, is given by

\[ \tan(\theta_c) = \frac{1}{\sqrt{n^2 - 1}} \quad \ldots 3.2 \]

Here, \( n = n_1/n_2 \). Computing the values of \( f_p \) and \( f_m \) by standard ray-tracing techniques, \( LSA \) can be calculated as

\[ LSA = R \left[ \frac{n}{n-1} - \frac{n}{\sqrt{n^2 - 1}} \right] (\theta > \theta_c) \quad \ldots 3.3 \]

Here, \( R \) is the radius of curvature of the lens and \( n \) is the refractive index of the lens material. We shall now first investigate the fundamental optical properties of lenses for different amounts of initial deflection, which includes focal length and LSA. Fig. 3.2. below depicts the focal lengths of spherical profiles for a given value of refractive index, 1.38. Each profile (in red), corresponds to a certain value of non-dimensionalized initial deflection defined as \( h/a \), here \( h \) is the initial deflection of the lens measured from the optical center and \( a \) is the aperture radius. As \( h/a \) decreases, the respective focal plane becomes more flat. Extrapolating this, if we have a perfectly flat interface with zero curvature, it will represent an afocal system with infinite focal length.

**Fig. 3.2.** Spherical lens profiles (red) and their corresponding focal planes (blue) for different values of initial lens deflection: 0.8, 0.5 and 0.2, measured from the optical center, along the optical axis. \( n = 1.38 \), is the refractive index of the lens material.

As it can be inferred from Fig. 3.3, the focal plane becomes flat for a hyperbolic lens profiles. This happens when the refractive index ratio, 1.38, matches with the eccentricity
of the lens profile. As the radial distance from the optical axis (for spherical and parabolic profiles in Fig. 3.3) increases, focal length decreases because of enhanced degree of refraction. Consequently, the corresponding distance of focal plane from the optical center decreases. Moreover, as the lens profile changes from spherical to parabolic, a degree of flatness is induced in the observed focal plane, which eventually becomes perfectly flat as the lens attains a hyperbolic profile with the eccentricity matching the refractive index ratio.

\[ n = 1.38 \]

Fig. 3.3. Spherical (red, \( e = 0 \)), parabolic (black, \( e = 1 \)) and hyperbolic (green, \( e = 1.38 \)) lens (refractive index = 1.38) profiles and their corresponding focal planes (blue). Closed symbols depict lens profile while open symbols denote their corresponding focal planes.

It is also worthwhile to study the distance from the optical axis, called impact distance, beyond which all the rays impinging on the lens undergo total internal reflection and are unrefracted. Fig. 3.4. below illustrates the variation of impact distance, with respect to the changing curvature for spherical lenses. As \( h \) increases from 0.7a to a, corresponding curvature also shoots up. It is evident from Fig. 3.4., that for deflections corresponding to 0.7a and 0.73a, all the rays undergo refraction. As the \( h \) is increased, rays experience total internal reflection as they hit the lens surface beyond the critical angle.
Finally, we plot in Fig. 3.5 the non-dimensionalized LSA against the radial distance for a given value of initial deflection. Similar conclusions can be deduced as construed from the previous plot. For 0.7a and 0.73a, LSA progressively increases with h/a, however, for 0.75a, 0.8a and a, it first attains a maximum and then gradually decreases. The point of inflexion represents the h/a corresponding to total internal refraction.

Before going further into the mathematical foundation of the wavefront aberrations, it is important to understand how an image is formed by an optical lens system. We shall undertake this task in the next section.

### 3.2 Image formation by an optical system

Consider an object with intensity distribution $I_0(y, z)$ (where $(y, z)$ is the coordinate system as defined in the object plane) as shown in Fig. 3.6., lying in the object plane, imaged through a lens system. The processed image is spread out on the image plane with an intensity distribution $I(Y, Z)$. Consider an infinitesimally small element $dy\,dz$ on the object plane. Its corresponding intensity distribution on the image plane is given by:

$$
\frac{dI}{dydz} = \epsilon(y, z; Y, Z)I_0(y, z)\,dy\,dz
$$

Here, $\epsilon(y, z; Y, Z)$ is the profile of the resulting irradiance distribution on the image plane. It is called the point spread function (PSF). The intensity distribution on the image plane due to the complete object is obtained by integrating the small chunks of individual elements on the image plane and is given by

---

**Fig. 3.4.** Impact distance vs. lens deflection for different values of deflection: a, 0.8a, 0.75a, 0.73a, 0.7a.

**Fig. 3.5.** Longitudinal spherical aberration vs. lens deflection for different values of deflection: a, 0.8a, 0.75a, 0.73a, 0.7a.
A point source is represented by a Dirac delta function. For a point source,

\[ I_0(y, z) = A \delta(y - y_0)(z - z_0) \] ..3.6

where \( A \) is the amplitude. Substituting this into above integral yields,

\[ I_i(Y, Z) = A \epsilon(y_0, z_0; Y, Z) \] ..3.7

**Fig. 3.6.** A point object on object plane: \((y, z)\) is imaged through an optical system on the image plane: \((Y, Z)\). Figure [11.16] taken from Eugene Hecht, “Optics”. The point spread function: the irradiance produced by the optical system with an input point source.

In diffraction limited systems, the Airy disc is defined as the irradiance distribution of a point object centred around a Gaussian image point. The radius of an airy disc is given by:

\[ A_r = \frac{1.22 \lambda}{D} \] ..3.8

where \( f \) is the focal length of the lens, \( D \) is the diameter of the lens and \( \lambda \) is the wavelength of the light source. It is important to reiterate as mentioned in chapter 2 that a system is said to diffraction-limited if the spot size as observed on the image plane lies entirely inside the airy disc. We shall exploit this concept frequently to characterize our optofluidic lenses in the forthcoming chapters.

The intensity distribution on the image plane can also expressed as convolution (denoted by *) of intensity distribution of object and the corresponding PSF.

\[ I_i(Y, Z) = I_0(y, z) * \epsilon(y, z) \] ..3.9

Here, we have used \( \epsilon(y, z) \) instead of \( \epsilon(y, z; Y, Z) \) as employed in equation 3.5. This is due to the fact that the numerical value of \( \epsilon(y, z; Y, Z) \) on image plane is related to its displacement from its central coordinates. Taking the Fourier transform on both sides and applying the convolution theorem, one can express the above equation as following
The optical transfer function, \( OTF \), is defined as the Fourier transform of PSF (Point spread function). Hence, \( OTF \) translates the spatial intensity distribution in its frequency domain.

\[
F[I_i(Y,Z)] = F[I_0(y,z)].F[\varepsilon(y,z)] \quad .3.10
\]

\[
F[\varepsilon(y,z)] = F[k_y, k_z] \quad .3.11
\]

\( OTF \) is a complex numerical quantity. Hence, \( OTF \) is composed of both real and imaginary parts. The modulus of \( OTF \) denotes its real part and is known as MTF or Modulation transfer function. MTF is explained in detail in section 2.2c) of chapter 2.

### 3.3 Wavefront characterization by Zernike polynomials

A wavefront is a locus of disturbance of points with constant phase. A collimated source of light generates a parallel wavefront while a point source of light produces a spherical wavefront. A ray is perpendicular to the wavefront. Consider a rotationally symmetric optical system, with the optical axis being the axis of rotational symmetry as shown in the fig. 3.7.

\[
F[3.7]. A point object \textbf{P} as imaged through an optical system forms an image at point \textbf{P}' . \text{EnP} \text{ represents Entrance pupil, ExP stands for Exit pupil, AS is the aperture stop, CR denotes the chief ray passing through the center of the entrance pupil and OA is the optical axis. Figure [3-6] taken from Virendra N. Mahajan, “Optical Imaging and Aberrations” .}
\]

Light emanating from the point source positioned at a distance \( h \) below the z-axis, passes through the entrance pupil, undergoes refraction from the optical system, passes through the exit pupil, finally forming an image at a height \( h' \) above the optical axis. The z-axis is along the optical axis, the x-axis is perpendicular to the z-axis going inside the plane of paper, while the y-axis is perpendicular to the two axes lying in the plane of paper. The z-y plane is the tangential plane while the z-x plane is the sagittal plane. The aperture stop (AS) restricts the amount of light eventually coming out of the system. The wavefront aberration function is defined with respect to a Gaussian reference sphere. The Gaussian reference sphere is in turn defined as a sphere passing through the center of exit pupil (O in Fig. 3.7) with its center lying at the Gaussian image point (\( P' \) in Fig. 3.7). Any departure of the
wavefront, as observed on exit pupil, from the Gaussian reference sphere, constitutes wavefront aberration. It is quantified by a wavefront aberration function $W(\rho, \theta)$, where $\rho$ and $\theta$ and the radial distance from the optical axis and the azimuthal coordinate. For a perfect unaberrated optical system, all rays entering into an optical system are focused at the Gaussian image point. Therefore, for a perfectly assembled optical system, exhibiting no optical aberrations, all rays emanating from point object $P$ should converge at point object $P'$. It is observed that even for most optimized diffraction limited systems, the precise conjugate behavior is not replicated in the image i.e. a point object does not form a point image, instead it forms an airy pattern with the intensity being distributed in the form of concentric circles. In practice, however, most optical system suffer from aberrations, which means rays at different locations in the exit pupil have different focal points. The traditional way of dealing with the optical aberrations is to represent the wavefront aberration functions in the form of so-called Seidel aberrations. Such representation is not yet obsolete and still holds relevance in the fundamental understanding of aberrations. However, with the advancement in the analytical techniques for assessing the optical aberrations, better mathematical formulations have been developed. It is desirable to decompose a wavefront aberration function into a set of orthogonal components so that each individual orthogonal coefficient can be independently studied. Zernike polynomials constitute such a set of orthogonal polynomials defined on a unit circle with remarkable mathematical properties, as we shall see later. The wavefront aberration function can be expanded into Zernike polynomials[1] defined as:

$$W(\rho, \theta) = \sum_{n=0}^{\infty} \sum_{m=0}^{n} c_{nm} Z_n^m(\rho, \theta)$$

where $c_{nm}$ are the orthonormal Zernike coefficients, $n$, $m$ and $n - m \geq 0$ and even, $n$ is the order and $m$ is the angular frequency. $c_{nm}$ depends on the image height $h'$. Each Zernike coefficient represents a certain kind of aberration (see Table 2.1. listing different kinds of aberrations). Zernike polynomials are expressed as a product of radial and angular terms.

$$Z_n^m(\rho, \theta) = [2(n + 1)/(1 + \delta_{m0})]^{1/2} R_n^m(\rho) \cos m\theta$$

where $\delta_{ij}$ is the kronecker delta. The radial term is given by

$$R_n^m(\rho) = \sum_{s=0}^{(n-m)/2} \frac{(-1)^s(n-s)!}{s!(n+m/2-s)!(n-m/2-s)!} \rho^{n-2s}$$

and is a polynomial of degree $n$ in $\rho$. The radial polynomials are even or odd in $\rho$ depending on whether $n$ and $m$ is even or odd.

$$R_n^m(1) = 1$$

$$R_n^m(\rho) = \rho^n$$
3.4 Properties of Zernike polynomials:

1. Zernike circular polynomials are orthogonal over a unit circle. This implies the orthogonalities of radial and angular functions:

\[
\int_0^1 R_n^m(\rho) R_{n'}^{m'}(\rho) \rho d\rho = \frac{1}{2(n+1)} \delta_{nn'} \quad .3.18
\]

\[
\int_0^{2\pi} \cos m\theta \cos m'\theta = \pi(1 + \delta_{mm}) \delta_{mm'} \quad .3.19
\]

This necessitates

\[
\int_0^1 \int_0^{2\pi} Z_n^m(\rho, \theta) Z_{n'}^{m'}(\rho, \theta) \rho d\rho d\theta / \int_0^1 \int_0^{2\pi} \rho d\rho d\theta = \delta_{nn'} \delta_{mm'} \quad .3.20
\]

The corresponding orthonormal coefficient of each Zernike term is given by:

\[
c_{nm} = \int_0^1 \int_0^{2\pi} W(\rho, \theta) Z_n^m(\rho, \theta) \rho d\rho d\theta / \int_0^1 \int_0^{2\pi} \rho d\rho d\theta \quad .3.21
\]

It is important to note here that there are indeed other polynomials, which are orthogonal over unit circle. However, only Zernike polynomials represent balanced aberrations.

2. Each Zernike aberration is composed of one or more classical Seidel aberrations. For example, Zernike spherical aberration is composed of primary spherical aberration, defocus and tilt. Similarly, Zernike Coma is composed of primary Seidel coma and tilt. The relative quantum of classical Seidel aberration present in each Zernike term ensures that each Zernike polynomial is orthogonal to the other.

3. The amalgamation of two or more aberrations employed in formulation of Zernike representation is known as balancing of aberrations. This ensures that aberrations are optimally balanced so as to yield minimum variance across the exit pupil.

4. Zernike representation of the wavefront is complete. This completeness implies that inclusion or exclusion of a particular Zernike term does not affect the other Zernike coefficients. Hence, the value of a particular Zernike coefficient is independent of the number of terms used to represent wavefront aberration.

5. The number of terms in Zernike expansion of a particular order \(n\) is

\[
N_n = [(n/2) + 1]^2 \text{ for even } n \quad .3.22
\]

\[
N_n = (n + 1)(n + 3)/4 \text{ for odd } n \quad .3.23
\]

6. The mean value of the aberration function is

\[
\langle W(\rho, \theta) \rangle = \int_0^1 \int_0^{2\pi} W(\rho, \theta) \rho d\rho d\theta / \int_0^1 \int_0^{2\pi} \rho d\rho d\theta = c_{00} \quad .3.24
\]

51
7. Mean square value of aberration function is given by

\[
\langle W^2(\rho, \theta) \rangle = \int_0^{2\pi} \int_0^1 W^2(\rho, \theta) \rho d\rho d\theta / \int_0^{2\pi} \int_0^1 \rho d\rho d\theta
\]

\[
= \sum_{n=0}^{\infty} \sum_{m=0}^{N} c_{nm}^2
\]

\[.3.25\]

8. Variance across the pupil is

\[
\sigma_w^2 = \langle W^2(\rho, \theta) \rangle - \langle W(\rho, \theta) \rangle^2 = \sum_{n=1}^{\infty} \sum_{m=0}^{N} c_{nm}^2
\]

\[.3.26\]

where \(\sigma_w\) is the standard deviation. This means that variance is simply the sum of squares of each Zernike coefficient. Hence, each Zernike coefficient represents the standard deviation of the corresponding Zernike aberration. This property enables us to calculate the Strehl’s ratio, which in turn is defined as

\[
S = \exp(-k\sigma_w^2)
\]

\[.3.27\]

where \(k\) is the wavenumber and \(\sigma_w^2\) is the variance as defined earlier.

3.5 Introduction to Zemax

Zemax is an optical simulation platform used for analysing the performance of optical systems on the basis of standard metrics of optical quality. The norms of optical quality are determined by MTF, RMS wavefront error, Strehl’s ratio etc. The first step is to build an optical setup invoking the lens data editor. The user interface of the lens data editor looks like as shown below:

![Illustration of Lens data editor (LDE) of Zemax simulation toolbox.](image)

Each column represents the geometrical or optical characteristic of the optical system corresponding to a particular row. The column headings have their usual meanings, e.g. surface type stands for the geometrical configuration of the optical element. The notation ‘standard’ means that the element is spherical in nature and is either concave or convex depending on the sign of radius of curvature. In case it is aspherical (even or odd), extra terms ‘conic’ and aspherical coefficients must be defined. As mentioned before, the conic constant is the negative of the square of the eccentricity. Thickness represents the distance between the outer edge of the current element to the inner edge of the very next element.
'Glass' is used to specify refractive index by selecting the requisite material enlisted in the Glass catalogues. Provisions for user defined materials are also available. Semi-diameter stands for the distance between the optical centre to either edge of the lens. The next step involves choosing the wavelength of the light. It can be monochromatic (of single wavelength) or polychromatic (composed of a number of different wavelengths). Specific weights can also be attached to respective wavelengths. It is essential to accurately specify the aperture. This can be done in typically five different ways.

1. Object cone angle = $\theta$: As shown in the fig. 3.8a, it is the half angle subtended by an object at the edge of the lens.
2. Numerical aperture, $NA = n \sin \theta$: Here, $n$ is the refractive index of the medium present in image space.
3. Entrance pupil diameter (EPD): It is defined as the diameter of the beam entering into the optical system as shown in fig. 3.8b.
4. Float by stop size: Aperture stop restricts the amount (size) of the beam entering into the optical system. In case of multi-component lens system, as shown in fig. 3.8b, it can be an internal iris, determining the quantum of rays eventually passing through it.
5. F-Number $= \frac{f}{D}$: It is defined as the ratio of focal length to the aperture size. This is illustrated in fig. 3.8a.

![Fig. 3.8. a) Various specifications of aperture for a single lens system: Cone angle, Numerical aperture, F-Number. b) Entrance pupil diameter defined for a multi-component system. Figure taken from Zemax Manual.](image_url)

Next one has to define an object or Field of view (FOV). This can be done in four different ways.

1. Angle: This is the angle subtended by an object at the centre of Entrance pupil.
2. Object height: The length of the object in specified units.
3. Paraxial Image height: Defined by specifying image height in image plane rather than object height. This is employed for systems having low distortions.
4. Real Image height: It is employed for systems having high distortions.
In a nutshell, the FOV can be the angle or can denote spatial extent on image plane. If aperture stop is not entirely filled, it causes pupil aberration. This results in incorrect determination of focal spot and consequently faulty analysis. It can be suppressed by enabling the Ray aiming feature available in the Zemax. It completely fills the stop till its edges suppressing any off-edge rays and arresting pupil aberrations.

The next step is optimization. It is important to mention here that the system is optimized for the parameters defined as variables in the lens data editor. For example, the distance between two optical elements defined as 'Thickness' in the LDE or the radius of curvature of a lens can be a variable. Commonly used tools are quick focus, quick adjust or slider. Quick focus adjusts the back focal distance for the best focus. Slider is employed for real-time visualization. The default optimization types are RMS spot size or RMS wavefront error. Optimizing an optical system on a particular merit, say spherical aberration or MTF etc. or combination of both, requires to explicitly define a Merit operand by invoking a merit function editor (MFE). In case of multiple merit operands, the merit function is defined as square root of sum of squares of individual merit operands. It is a numerical representation of how closely an optical system meets specified set of goals. Notationally,

\[ M_i = \sqrt{\frac{\sum W_i(V_i - T_i)^2}{\sum W_i}} \] ... 3.28

Here, \( W_i \) is the attached weight, \( V_i \) the calculated value and \( T_i \) the target value. Hence, \( M_i \) is always positive. Perfectly optimized optical systems should have an \( M_i \) value of zero. The objective of local optimization using the “DLS” algorithm is to drive the merit function close to zero. Any departure of \( M_i \) from zero on positive scale, signifies degradation in the optical performance of the system based on the specified merit. More than 300 merit operands are available in Zemax. For example defining transverse ray aberration (TRA) in the merit function for optimization minimizes the RMS spot size. It is required for a predefined spatial extent of the image. It is customary to use Default Merit function as spot size, in case one has to capture the entire image on a detector of well-defined size. Otherwise, Wavefront Error (WFE) is employed as Default Merit function. Customized operands can also be constructed by formulating the same using Zemax programming language (ZPL).

Spot diagram and MTF are the most widely used merit norms in determining the optical quality of an image. Spot diagram represents the distribution of rays on the image plane. It has two facets: first is GEO radius and second is RMS Radius. GEO radius is the radius of the circle formed by the most off-axis ray on the image plane. RMS radius, on the other hand, is a more accurate reflection of the spatial extent of the rays impinging the image plane. However, it is important to note that all optical systems, including the most ideally optimized, are diffraction limited. An optical system is called diffraction limited when its performance is limited by the physical effect of diffraction rather than imperfections in design or fabrication. There are three general criteria for diffraction limited systems:

1. Peak to valley wavefront error is less than one quarter of a wave (Rayleigh criterion).
2. Geometrical spot diagram is contained within the Airy disc.
3. High numerical value of Strehl’s ratio (e.g. > 0.8).

The other important criterion, MTF is explained in detail in the previous sections. One can also calculate the quantitative contribution of each optical aberration and its impact on the image formation. This can be easily accessed by noting the corresponding Zernike coefficients. Let’s revisit the construction of merit function as explained earlier. In our case, as we shall subsequently see in the coming chapters that Zernike spherical aberration coefficient is evaluated under zero defocus condition. Hence, defocus aberration will be defined as the merit function. The optimization routine will calculate the focal length, defined as a variable in the lens data editor under zero defocus. It is important to note that all optical properties are calculated with respect to a reference wavefront, which can be planar or spherical. Planar wavefront can be chosen as reference by invoking afocal mode.

3.6 Conclusions

The tools and methods explained in this chapter shall be extensively employed in the forthcoming chapters for analyzing our optofluidic lenses. This chapter lays the foundations and essential criteria on the basis of which we shall analyze the performance of our liquid lenses. We shall compute the spherical aberrations of liquid lenses and report their other pertinent optical properties. The standard metrics discussed here, shall serve as a guiding principle for judging the optical quality of our lenses.

References

Chapter 4

Optofluidic lenses with tunable focal length and asphericity

Abstract
In this chapter, we demonstrate that a liquid-liquid interface can be electrostatically modulated into a tunable and ideal aspherical lens by applying an electric field to a drop entrapped in an aperture. The drop actuation is controlled by two pressure stimuli: hydrostatic pressure and electrical Maxwell stress. Experiments are conducted in insulating silicone-oil ambient with conducting aqueous cesium iodide solution as drop phase. Electrostatic pressure alters the curvature of initially spherical drop meniscus, consequently changing marginal and paraxial focal lengths and thus reducing the longitudinal spherical aberration (LSA). Focal lengths and LSA are determined from captured meniscus profiles. An ideal lens is obtained when the eccentricity of the fitted profile is equal to the refractive index ratio of the two media. Finally, we successfully demonstrate the concept by optically imaging a square grid.
4.1 Device fabrication

**Fig. 4.1.A)** Schematic of the device. Curvature of drop is regulated by hydrostatic head $\Delta P_h$ through a needle inserted in the O-ring. Voltage $U$ is applied between the aperture plate and top electrode. Inset shows the underlying fabrication process, a copper washer (brown) of 1mm inner diameter is glued axis-symmetrically on the top of a 1.2mm aperture, followed by gold and thiol deposition (**Left**). Photograph of the device. Device connected with hydrostatic head and wires for regulating backpressure and applying voltage respectively (**Inset**) **B)** Drop profiles of perfect aspherical lens with zero LSA when voltage is applied and spherical lens at zero voltage. Optical images of the square grid as imaged through the perfect aspherical and spherical lens. The flat topography of square grid is restored by applying the voltage and simultaneously regulating the hydrostatic pressure (**Right**).

Fig. 4.1A) illustrates the Schematic of the device. The device consists of an O-ring filled with conducting aqueous cesium iodide solution sandwiched between a bottom ITO electrode and a gold coated aperture plate with an orifice of diameter 1.2mm. Silicone-oil is used as an insulating ambient fluid. The refractive index ratio is 1.10. Because of the density-matched system, the Bond number is low and hence the effect of gravity can be neglected. Conducting experiments in fluidic ambience also arrest evaporation. In order to have optically smooth aperture, devoid of any rough aberrations, copper hole grid of 1mm internal diameter and 3.05mm external diameter is glued coaxially on the top of 1.2mm aperture. This assembly is then subjected to gold deposition, thus making the top surface of the aperture plate conducting. In order to pin the contact line at the aperture, we deposit thiol on the aperture plate by immersing it in dilute thiol solution of 99% ethanol for 24 hrs. This hydrophilic-hydrophobic interface provides excellent pinning at the aperture corners with minimal contact line movement. The drop meniscus in the aperture is created by hydrostatic pressure via a needle inserted in the O-ring. By varying the height of hydrostatic head, the back pressure and hence the initial meniscus deflection of the formed drop can be tuned. A 2mm glass spacer is provided between aperture plate and top electrode. The meniscus is deflected by applying a voltage between aperture plate and top electrode. The experiments are conducted by creating a liquid meniscus in an aperture and changing its asphericity by applying electric field. The curvature at zero voltage is controlled by hydrostatic head. Essentially, we have two control parameters, the voltage and the
backpressure. The synchronized manipulation of the two, can yield a perfect lens. Fig 4.1B) shows spherical vs. aspherical drop profiles at zero voltage and at a specified voltage $U$ respectively. Next to these profiles is a square grid imaged through the liquid lens, with and without applying voltage respectively. The captured images clearly manifest how electric field combined with Laplace pressure can be employed in arresting spherical aberration. Not only LSA is corrected, but also distortion is rectified. The bottom image shows a square grid imaged at zero voltage through a spherical meniscus. However, as the voltage is increased to 2.18kV, the distortions in the shape of the square grid, because of inherent aberration, are suppressed. Equilibrium shapes of the lens profiles are determined by the local balance of electrical Maxwell stress and Laplace pressure. At equilibrium, the local Laplace pressure at any infinitesimal point on the deformed meniscus is equal to the local Maxwell stress. Hence, local Laplace pressure and in turn, local Maxwell stress can be computed for each equilibrium profile by considering the lens configuration in an axis-symmetric cylindrical co-ordinate system. This is given by:

$$\Delta P_h = \gamma \left[ -\frac{x_{rr}}{(1+x_r)^2} + \frac{1}{z(1+x_r)^{3/2}} \right] - \frac{1}{2} \varepsilon_0 \varepsilon \varepsilon_\text{r} E_n^2$$

where $\Delta P_h$ is the hydrostatic pressure, $z$ is the along the direction of optical axis, $r$ is the radial direction, $\varepsilon_0$ is the permittivity of the free space, $\varepsilon$ is the dielectric constant of the ambient fluid and $E_n$ is the local electric field normal to the interface. The electric field inside the conducting drop phase is zero.

4.2 Lens characterization

![Diagram of lens characterization](image)

**Fig. 4.2. Lens characterization.** P on the principal axis corresponds to the paraxial focus. The ray striking the periphery of lens meniscus, called marginal ray (in orange), hits the principal axis at the marginal focus M. PM is defined as the Longitudinal spherical aberration (LSA). In this case, it is positive as the paraxial focus lies ahead of marginal focus.
Drop profile extraction and fits: Drop profiles are extracted from the recorded images by taking the gradient of the intensity variation across the liquid-liquid interface in each pixel row. The intensity across the interface is sigmoidal in nature, while its gradient is Gaussian. The drop profile is obtained by connecting the peaks of the fitted Gaussian curves at each scan line. Characterization of aspherical lenses is done by subsequently fitting the extracted meniscus profile with the following standard conic surface equation.

\[ y = \frac{R}{e^{\frac{1}{2}} - 1} \left[ \sqrt{1 + \left( \frac{(e^2 - 1)y^2}{R^2} \right)} - 1 \right] \]

Here, radius of curvature \( R \) at the apex and eccentricity \( e \) are the fitting parameters. The fit thus yields the value of eccentricity \( e \) from which the nature of the conic section can be inferred. A perfect lens is obtained when the relative value of refractive index matches with the eccentricity of the fitted profile[1]. Red line in Fig. 4.2. is the conic section fit. For a positive lens, the refractive index ratio of the drop phase to that of ambient phase must be greater than 1. This implies \( e \) to be greater than 1. Hence, a hyperbolic drop profile with \( e \) equal to the refractive index ratio gives the perfect lens. LSA is the difference between paraxial focus and marginal focus as measured from the optical center. For a perfect lens, with zero spherical aberration, LSA is zero.

4.3 Measurement of focal length and LSA

Focal length and LSA are calculated by a ray-tracing code written in MATLAB. The marginal focal length is defined as the distance between the optical center and the point where most off-axis marginal ray, beyond which there will be total internal reflection, strikes the optical axis. The paraxial focal length is given by \( f_p = R/(n - 1) \). The distance between the two is defined as LSA.

The top graph in Fig. 4.3A) compares the experimental vs. numerical spherical profiles for different values of backpressure at zero voltage. The bottom graph in Fig. 4.3A) compares the numerical profiles with the experimental ones for three different drop profiles at 1400, 1600 and 1700V starting from zero backpressure, i.e. from a perfectly flat interface. As evident, the two experimental and numerical profiles overlap. Numerical profiles in Fig. 4.3A) are calculated by a self-consistent calculation of the electric field distribution and the shape of the oil-water interface using a finite element method as implemented in the commercial software package COMSOL MULTIPHYSICS using an axisymmetric coordinate system[2]. The conductive water phase as well as the gold coated middle aperture plate are kept at zero potential. The flat top electrode is kept at the fixed applied potential (see Fig. 4.1A). The electric field inside the conducting drop phase is zero. The electric field distribution in the oil phase, between the liquid meniscus and top electrode, with relative dielectric permittivity \( \epsilon \epsilon_0 \), is obtained by solving the Laplace equation in the ambient fluid computational domain. Numerical profiles are obtained by setting the local balance of Maxwell stress and Laplace pressure along the liquid-liquid interface (Eq. 1). The evolving interface is tracked using a moving mesh algorithm (Arbitrary Lagrangian Eulerian; ALE).
Fig. 4.3. Experimental (in black) versus numerical (in color) surface profiles for spherical interfaces at zero voltage for increasing hydrostatic pressure 30Pa, 68Pa and 88Pa (top left) and for aspherical interfaces at zero hydrostatic pressure for increasing voltage 1400V, 1600V and 1700V (bottom left) [Figure 4.5 is taken from Gor Manukyan’s PhD thesis titled “Electrical manipulation of liquids at interfaces”]. Corresponding drop images (Middle column) and their extracted interface fits (in red). Variation of paraxial radius of curvature $R$ (in blue) and LSA (in red), for spherical profiles at zero voltage as hydrostatic pressure is increased from 30Pa to 88Pa (top right) and for aspherical drops as the voltage is ramped up and down (bottom right). $\Delta U = U_{\text{max}} - U$ where $U_{\text{max}}$ is the maximum voltage for each of the ramps. DC voltage is applied at the ramp frequency of 0.05Hz. Light symbols (in red) correspond to $\Delta P_h = 68 \text{ Pa}$, dark symbols (in red) to $\Delta P_h = 88\text{ Pa}$.

The top graph in Fig. 4.3C) depicts the variation of Radius of curvature $R$ and corresponding LSA for spherical drop profiles at zero voltages. It is evident that as $R$ decreases, or as curvature of the spherical lens increases, LSA also increases. This is intuitively true because, for less curved interfaces, an optical ray impinging on the interface suffers a lower degree of refraction and hence the difference between marginal and paraxial focal lengths, which is defined as LSA, is considerably less. Tunability in focal length is presented in the bottom graph in Fig. 4.3C). As the voltage is increased, paraxial and marginal focal length decrease, falls to a minimum value at the maximum voltage and then re-attains its initial value upon decreasing the voltage to 0. (This is shown for multitude of cycles in the in Fig. 4.4). Red dots feature how the LSA varies correspondingly. It initially decreases, passes through zero, where LSA is completely suppressed, after which it depreciates to a minimum, assuming negative value and then regains its initial value in the upward voltage cycle. Crest and troughs correspond to maximum and minimum values of
the measured quantities respectively. Each point on the plot signifies the equilibrium position when Laplace pressure equals Electrical Maxwell stress. A perfect lens is obtained when the relative value of refractive index matches with the eccentricity of the fitted profile. LSA varies from 1.13mm to -0.16mm for 88Pa initial backpressure as voltage is ramped from 0kV to 2.48kV and from 0.82mm to -0.51mm for 68Pa as voltage is increased from 0kV to 2.70kV. For each value of initial backpressure, there exists a maximum possible attainable voltage (critical voltage), with stable meniscus. Critical voltage decreases with increase in initial backpressure. Above critical voltage, it so happens that LSA stoops to a negative value. This is observed when the eccentricity ‘e’ of the extracted profile exceeds the refractive index ratio. The two plots of fig. 4.3C), shown in light (blue and red) and dark (blue and red) correspond to two different values of backpressures. We observe that at lower values of backpressure, the two focal lengths (paraxial and marginal) intersect and hence LSA attains large negative values. However, at higher values of backpressure, LSA just approaches zero values. Indeed, at even higher backpressures, LSA will not be completely subsided.

The unaltered landscape of focal lengths in Fig 4.4, even after several number of voltage cycles corroborates our claim of long-term reversibility. It implies that morphology of the lens at any particular time remains unchanged.

**Fig. 4.4.** Paraxial focal length (light green) and Marginal focal length (light pink) plotted against time for two voltage cycles.
4.4 Variation of focal length with applied voltage

**Fig. 4.5.** Focal length vs. the applied voltage squared (blue symbols) for a range of hydrostatic pressures increasing from 30Pa to 88Pa (top to bottom) as indicated by the arrow and the color gradient of the blue symbols. The dark green curve connects the lenses with zero LSA thus separating regions of positive (in blue) and negative (in red) LSA. Drop images with extracted fits at zero LSA for $\Delta P_h = 50Pa$, 68Pa and 88Pa for the three encircled data points.

The plot 4.5. depicts the variation of paraxial focal length versus the square of the voltage for differential Laplace pressures (backpressures) of 30Pa, 34Pa, 41Pa, 50Pa, 56Pa, 68Pa, 77Pa, 88Pa corresponding to eight different values of initial meniscus deflection. The above plot can be divided into two regimes, the light blue part corresponding to the positive values of LSA while the light pink part signifies negative LSA values. The smooth green curve, segregating the two regimes, represents the aspherical lens profiles with zero LSA values. Paraxial focal length falls sharply as initial Laplace pressure is increased because of a decrease in the value of radius of curvature. Erratic behavior is observed at low values of initial deflection because of inappropriate fitting (Not shown in Fig. 4.5). However, it turns out to be more regular at higher values of initial Laplace pressure. Clearly, marginal focal length also decreases as voltage is increased. For much higher values of initial deflection, it is not possible to attain zero LSA as we reach the critical maximum voltage prior to hitting zero LSA values. Fig. 4.5b) also shows three aspherical drop images, which are perfect lenses. The color assignment (orange, black and green) bordering the drop images correspond to three specific locations on the plot.
<table>
<thead>
<tr>
<th>$\Delta P_t$ [Pa]</th>
<th>LSA Range [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>0.28 - 1.79</td>
</tr>
<tr>
<td>34</td>
<td>0.34 - 1.46</td>
</tr>
<tr>
<td>41</td>
<td>0.43 - 0.92</td>
</tr>
<tr>
<td>50</td>
<td>0.55 - 0.99</td>
</tr>
<tr>
<td>56</td>
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<td>68</td>
<td>0.82 - 0.51</td>
</tr>
<tr>
<td>77</td>
<td>0.98 - 0.28</td>
</tr>
<tr>
<td>88</td>
<td>1.13 - 0.16</td>
</tr>
</tbody>
</table>

Table 4.1. Range of attainable LSA’s as voltage is ramped up from 0V, starting with spherical meniscus, for different values of initial backpressures.

4.5 Discussion

The functionality of a liquid-liquid interface as a viable and tunable adaptive fluidic lens, modulated electrostatically and regulated hydrostatically, is demonstrated. Our research provides a solution to the problem posed by customized solid lenses—non-tunability. It is achieved by manipulating the meniscus shape by combining electrostatic force and Laplace pressure (backpressure). An important facet to be considered for the sustainable functioning of the device is the power requirement. Top electrode and middle plate together constitute a parallel plate capacitor with silicon oil as a dielectric medium. The dielectric constant of silicon oil is 2.5, the gap between the plates is 2mm, and the area of the top ITO electrode plate is $2.5 \times 1.5 \text{cm}^2$. This yields a capacitance of $4.425 \times 10^{-12} \text{ F}$. Owing to very small capacitance in our system and high DC resistance, we have low currents and hence power requirements are much smaller. Even at a modulation frequency of 1kHz, currents are within the mA range limiting power requirements to less than 1mW. Viscous losses can be further minimized by reducing the viscosity of the two media, preferably of the ambient fluid. The design has a lot to offer in terms of flexibility. Voltage requirements can be considerably reduced by increasing the aperture size, using combination of liquids with lower interfacial tension and also by reducing the distance between the top electrode and aperture plate. Multiple apertures can be integrated to form a parallelized aspherical microlens array. In contrast, miniaturization of the device is also feasible. However, this may amount to higher energy requirements because of an increase in Laplace pressure due to small aperture size. Dynamic response and switching speed of the lens, by altering the viscosities of the fluids and voltage frequencies and their subsequent effects on lens performance can be further explored. Optical characterization of lens by shack-Hartmann sensor will be the next step to reaffirm our findings.
Acknowledgement

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References

Chapter 5

Numerical analysis of electrically tunable aspherical optofluidic lenses

Abstract

In this work, we use the numerical simulation platform Zemax to investigate the optical properties of electrically tunable aspherical liquid lenses, as we recently reported in an experimental study [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, 6378 (2014)]. Based on the measured lens profiles in the presence of an inhomogeneous electric field and the geometry of the optical device, we calculate the optical aberrations, focusing in particular on the Z11 Zernike coefficient of spherical aberration obtained at zero defocus (Z4). Focal length and spherical aberrations are calculated for a wide range of control parameters (fluid pressure and electric field), parallel with the experimental results. Similarly, the modulation transfer function (MTF), image spot diagrams, Strehl’s ratio, and peak-to-valley (P–V) and root mean square (RMS) wavefront errors are calculated to quantify the performance of our aspherical liquid lenses. We demonstrate that the device concept allows compensation for a wide range of spherical aberrations encountered in optical systems.
5.1 Introduction

Optical aberrations are usually encountered in areas like imaging, photography, and microscopy. Their presence degrades the optical quality of the captured image, rendering it unfit for use in many professional applications. In order to mitigate optical aberrations, it is often necessary to build more complex optical systems composed of multiple optical elements. Of all the optical aberrations commonly observed, spherical aberration is the most fundamental. In microscopy, for example, specimens are routinely imaged through coverslips, which induce considerable spherical aberration. In order to compensate for this, one has to resort to either immersion objectives, such that the refractive index of the imaging medium is equal to that of the glass coverslip, or to dry objectives, in which a correction collar is employed to minimize the aberration. This is particularly true for high NA objectives, which require correction collars that have to be adjusted all the time [1]. This makes the optical systems bulky, difficult to build, and also expensive. Moreover, industrially manufactured solid lenses have a fixed focal length and are non-tunable in nature.

Adaptive optics overcomes these constraints by providing lenses with tunable focus. Liquid lenses, in this context, have attracted considerable attention in recent years due to their tunability and aberration control [2-8]. Various stimuli such as pressure, mechanical stresses, contact angle and electric fields can be used to tune liquid lenses into different shapes. While most approaches lead to spherical lens shapes with tunable radius and thus focal length, suitably designed elastically deformable materials [9,10] as well as inhomogeneous electric fields [2,11,12] have been shown to provide aspherical lens shapes. Zhan et al. [11] and Kuo and Lin [12] were the first to use the latter approach by curing drops of a UV-curable polymer precursor in the presence of an electric field. While this approach allows for generating lenses of various degrees of asphericity, their approach has two disadvantages: first of all, the tunability of the optical properties is obviously limited to the fabrication process. Once cured, the shape of the lenses is fixed. Second, the deformation of drops of fixed volume in a variable electric field leads to a coupled variation of the focal length and the asphericity. In our recent publication [2], we overcome both of these limitations by using truly liquid lenses for imaging purposes and – more importantly – by controlling the pressure in the lens in addition to the electric field. Thanks to the addition of this second control parameter, both focal length and the asphericity can be tuned independently within a wide range of parameters [2].

Various numerical schemes have been proposed to evaluate spherical aberration. Optical simulation platforms, such as Zemax, are routinely employed to design aspherical lenses [13,14] and spherically corrected achromatic variable-focus liquid lenses [15] for superior optical performance. Such tools offer the opportunity to estimate the optical properties of lenses in order to gauge their optical performance prior to construction. They also give us flexibility to optimize the design parameters according to specific customized requirements. Intra-ocular lenses [16] have also been designed and developed using Zemax to provide solutions in ophthalmic applications. Fuh and Chen [17] designed and constructed an optical system comprising an aspheric PDMS lens with aberration control properties. Lima et al. [18] numerically estimated the optical properties of electrically tunable astigmatic lenses. This was achieved employing a stripe electrode, thereby introducing rotational asymmetry in the lens meniscus, which was eventually manifested in the astigmatic behavior of the lens. Such
lenses are of potential use in correcting ocular astigmatism. Continuous zoom lenses [19] with real time MTF evaluation and achromatic GRIN singlet lenses [20] have also been conceptualized in Zemax.

In this work, we employ Zemax to analyze the optical performance of our electrically tunable aspherical lenses, as reported by Mishra et al. [2]. There, we presented a design and demonstrated experimentally that spherical aberration can be suppressed by the application of a voltage. However, the characterization of the optical properties of liquid lenses was rather crude: we simply calculated the longitudinal spherical aberration (LSA) by comparing the focal length of the paraxial beams and marginal beams based on side-view images of the liquid-liquid interface and the refractive indices of the two phases. This is a rather incomplete estimate, which ignores various other parts of the device, such as the unavoidable top and bottom plates covering the liquid lens. Here, we present a complete picture of the lens characterization, by investigating wavefront aberrations—specifically, Zernike spherical aberration (Z11)—and other pertinent optical properties, such as modulation transfer function (MTF) and image spot size. Z11 is calculated in units of waves, signifying the phase difference.

5.2 Methods

We analyzed the optical properties of our device based on the captured side-view images of the liquid lens, by extracting their respective surface profiles, fitting them with a conic section, and extracting their geometrical properties: eccentricity and radius of curvature at apex. Figure 5.1a) depicts the schematic of the experimental setup employed by Mishra et al. [2]. The device consists of a top glass plate (light blue in Fig. 5.1a)) with a thin transparent ITO electrode (not shown in Fig. 5.1a)), gold-coated aperture plate (dark yellow in Fig. 5.1a)) and bottom glass plate (white in Fig. 5.1a)). Conductive aqueous lens fluid (blue in Fig. 5.1a)) is entrapped in an O-ring (black in Fig. 5.1a)), sandwiched between the aperture plate and bottom glass plate, and an electrically insulating phase (yellow in Fig. 5.1a)) of silicon oil is contained between the aperture plate and top glass plate. Lens meniscus is created via hydrostatic pressure in an ambient silicon oil environment. The aperture diameter is 1 mm, and the distance between the aperture plate and top electrode is 2 mm. The meniscus is pinned along the aperture by a hydrophobic-hydrophilic contact.

Fig. 5.1. a) Schematic of electrically tunable optofluidic lens setup. A spherical lens created via hydrostatic pressure ($\Delta P_b$) is deformed into an aspherical shape by an application of a voltage ($U$) between the aperture plate and top electrode. Red curves spanning between the aperture plate and top electrode signify electric field lines. b) Side-view of aspherical lens under an applied voltage. The red curve shows the conic section fit.
The lens shape is controlled by two driving mechanisms: hydrostatic pressure and electric field. The meniscus profile at zero voltage is manipulated by simply tuning the hydrostatic pressure. The asphericity in the lens meniscus is induced by applying the voltage between the aperture plate and top electrode. The aqueous phase is kept at a fixed potential throughout the experiment. The ratio of refractive index of lens fluid to ambient silicon oil is 1.10. Further details of the lens device can be found elsewhere [2]. Figure 5.1b) shows a side-view of one such aspherical lens under an applied voltage.

Oh et al. [21] investigated the evolution of liquid interface into aspherical configurations of varying eccentricities under the influence of an electric field. The equilibrium lens profiles is determined by the balance of the applied hydrostatic pressure \( P_h \), the Laplace pressure \( \Delta P_L = 2\gamma\kappa(r) \) (\( \gamma \): surface tension; \( \kappa(r) \): local curvature of the interface) and the local Maxwell stress \( \Pi_{el}(r) = \varepsilon_0\varepsilon E^2 / 2 \) according to:

\[
P_h = 2\gamma\kappa(r) - \Pi_{el}(r)
\]

(\( \varepsilon_0 \) is the dielectric permittivity of the oil. \( E(r) \) is the electric field at the location \( r \)). Roghair et al. [22] formulated a numerical scheme to compute such equilibrium interfaces between conductive and non-conductive fluids.

Figure 5.2 illustrates the optical simulation setup, in which each element of the lens device (shown in Fig. 5.1a) is represented by a corresponding section of the similar material with its geometric thickness and shape as well as refractive index (note that the dimensions in Fig. 5.2a are not to scale). The objective is to characterize the optical performance of the lens device for variable hydrostatic pressure \( \Delta P_h \) and voltage \( U \) by calculating the Zernike spherical aberration (Z11) under zero defocus (Z4) conditions. The experimental values of lens meniscus curvature, aperture size, and eccentricity, along with other device parameters—such as the thickness and refractive index of the glass and the distances between the subsequent optical elements—are defined as constant input parameters in the lens data editor (LDE) of the Zemax simulation toolbox. Green light at \( \lambda = 534\text{nm} \) is employed in the simulation to illuminate the lens aperture. The following table summarizes the materials, thicknesses, and refractive indices of the various lens device mediums.

<table>
<thead>
<tr>
<th>Section Number</th>
<th>Material</th>
<th>Thickness (mm)</th>
<th>Refractive index</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Glass</td>
<td>1</td>
<td>1.51</td>
</tr>
<tr>
<td>2</td>
<td>Silicon oil</td>
<td>2</td>
<td>1.40</td>
</tr>
<tr>
<td>3</td>
<td>Conductive aq. solution</td>
<td>1</td>
<td>1.55</td>
</tr>
<tr>
<td>4</td>
<td>Glass</td>
<td>1</td>
<td>1.51</td>
</tr>
</tbody>
</table>

*Table 5.1. Specifications of lens device sections: material, thickness and refractive index.*
The distance between the top glass plate (1) and point object \( f_0 \) is defined as the variable and is optimized for zero defocus. The distance between the bottom glass plate (4) and image plane (5) is kept stationary for all the simulations. \( Z_{11} \) is evaluated with respect to a reference planar wavefront. Any particular optical system is optimized for its particular optical merit as defined by merit function. In our case, defocus aberration \( Z_4 \) is the merit function. The optimization routine is executed to estimate the optimized numerical value of \( f_0 \) for \( Z_4 \) equal to zero. The optimized value of the variable \( f_0 \) is calculated for the different values of hydrostatic pressure \( \Delta P_h \) and voltage \( U \).

**Fig. 5.2.** Simulation set-up of an optofluidic lens device in Zemax. A liquid lens is produced by hydrostatic pressure through an aperture of 1-mm diameter. Sections of the device are numbered as follows: 1-Top glass plate with 30-nm coated ITO, 2-Silicon oil, 3-Electrically conductive aqueous solution, 4-Bottom glass plate, and 5-Image plane. The material, thickness, and refractive indices of the device sections are summarized in Table 1.

In simulations, the \( f_0 \) lies in air. Compared to our previous estimate [2], in which we calculated the longitudinal spherical aberration (LSA) solely on the basis of the shape of the lens surface, this analysis also includes the optical effect of the top and bottom glass plates, which are integral elements of the actual lens device. Moreover, by calculating \( Z_{11} \), we quantify the actual wavefront aberrations, whereas the LSA merely signifies geometrical aberrations.

### 5.3 Results and discussions

Figure 5.3a) illustrates the lens profiles as extracted from the side-view images captured under different combinations of \( \Delta P_h \) and \( U \). Figure 5.3b) depicts the variations of \( Z_{11} \) and \( f_0 \) against the applied hydrostatic pressure. At zero voltage, the drop assumes a spherical cap shape with a radius \( R \), as required by the balance of the Laplace pressure \( \Delta P_L \) and the hydrostatic pressure, i.e. \( \Delta P_L = \frac{2\gamma}{R} = P_h \). As the hydrostatic pressure \( P_h \) is increased, the curvature of the lens meniscus increases, retaining its spherical character. Consequently, \( f_0 \) decreases, which in turn enhances spherical aberration. This is evident from Fig. 5.3. As hydrostatic pressure is increased from 30 Pa to 88 Pa at zero voltage (\( U = 0V \)), \( f_0 \) changes from 14.3 mm to 3.59 mm. Simultaneously, \( Z_{11} \) increases from 0.015 waves at 30 Pa to 0.38 waves at 88 Pa. As \( U \) is raised, the shape of the lens changes from spherical at 0V to aspherical configurations at higher voltages. This is clearly evident in Fig. 5.3a), where, starting from the spherical meniscus at 0 V, the lens assumes aspherical profiles at higher voltages. These trends are consistent with the results reported by Mishra et al. [2], where the LSA was shown to increase with the hydrostatic pressure for a spherical lens shape at zero voltage. Similar trends in focal lengths and Zernike spherical aberration (\( Z_{11} \)) are observed as a finite voltage is applied between the aperture plate and top electrode. For \( U \neq 0V \), the meniscus assumes aspherical
shapes with changing eccentricities. For \( U = 1.73 \, kV \), \( f_0 \) (open circles) varies from 10.96 mm to 2.52 mm, while \( Z_{11} \) (closed circles) changes from \(-0.069 \) waves to 0.35 waves. Similarly, for \( U = 2.45 \, kV \), \( f_0 \) (open triangles) varies from 7.38 mm to 0.97 mm, and \( Z_{11} \) (closed triangles) varies from -0.24 waves to 0.085 waves. Clearly, as is evident from Fig. 5.3b), for \( U \neq 0V \), the \( Z_{11} \) coefficient initially assumes negative values. As we increase the \( \Delta P_h \), \( Z_{11} \) eventually attains positive values.

![Fig. 5.3. a) Lens profiles at \( \Delta P_h \) = 30 Pa (blue), 56 Pa (green), and 88 Pa (red) for different values of \( U: 0 \, V \) (top), 1.73 kV (middle), and 2.45 kV (bottom). b) Variation of \( f_0 \) (open symbols) and Zernike spherical aberration (closed symbols) versus \( \Delta P_h \) for \( U= 0V \) (squares), 1.73 kV (circles), and 2.45 kV (triangles).]

![Fig. 5.4. Variation of \( f_0 \) with voltage squared (blue circles) for ranges of \( \Delta P_h \) = 30 Pa, 34 Pa, 42 Pa, 50 Pa, 56 Pa, 68 Pa, 77 Pa, and 88 Pa. Increasing the color gradient of blue circles delineates increase in hydrostatic pressure. The green curve depicts lens profiles with zero values of \( Z_{11} \). Red lines connect the profiles of the \( Z_{11} = -0.1 \) waves and the \( Z_{11} = 0.2 \) waves, while magenta lines show the profiles of the \( Z_{11} = 0.1 \) waves and the \( Z_{11} = 0.2 \) waves.]
Figure 5.4 shows the variation of $f_0$ against the square of $U$ for various initial values of hydrostatic pressures. Upon applying a voltage between the top electrode and aperture plate, the optimized value of $f_0$ decreases as the point source moves towards the top electrode. In the process, the lens assumes a hyperbolic shape, with its eccentricity matching the ratio of the refractive index of the lens fluid and ambient silicon oil, thus producing a perfect lens with minimum spherical aberration. The entire plot can be divided into two broadly distinct zones, one with positive values of the Zernike spherical aberration coefficient ($Z_{11}$) and the other with negative values. The former corresponds to surface profiles with eccentricities less than a perfect aspherical lens, the latter to higher eccentricities. The green line connects the meniscus profiles with zero values of $Z_{11}$. Hence, such lenses exhibit superior optical quality. The two red lines connect the negative values of the $Z_{11} = -0.1$ waves and of the $Z_{11} = -0.2$ waves. Similarly, the magenta lines connect the positive values of the $Z_{11} = 0.1$ waves and of the $Z_{11} = 0.2$ waves.

It is important to note the effect of the top and bottom glass plates on the numerical values of $f_0$ and $Z_{11}$. Changing the thickness of the top and bottom plates or simulating the device under the semi-infinite oil and water phase results in a focal shift; that is, it changes the value of $f_0$. However, the values of $Z_{11}$ remain approximately the same. For example, by changing the thickness of the top plate from 1 mm to 2 mm at 68 Pa under the applied voltage of 2.24 kV, $Z_{11}$ changes insignificantly from 0.08586 waves to 0.085233 waves, and $f_0$ changes from 2.96 mm to 2.28 mm. However, the numerical value of the $Z_{11}$ coefficient remains unaltered by varying the thickness of the bottom plate.

In order to further assess the optical quality of our liquid lenses, we generated the modulation transfer function (MTF) curves to quantify their resolution. Figure 5.5a) shows the MTF plot for spherical lenses at four different values of $\Delta \Phi_r$. MTF is plotted against the angular frequency for different values of initial hydrostatic pressures. The black curve signifies the diffraction-limited system corresponding to the best resolved system under given design constraints. The higher the departure of the MTF curve from the diffraction-limited black curve, the larger the spherical aberration and hence more degenerated the optical quality [23]. It is evident from the plot that MTF degrades with increasing backpressure. This is in agreement with the fact that an increase in backpressure aggravates the spherical aberration of the lens meniscus, thus producing optically inferior lenses with substantially reduced MTF.

However, as a voltage is applied between aperture plate and top electrode, the spherical aberration reduces and is perfectly compensated at a specific hyperbolic shape, producing an MTF curve approaching the diffraction-limited curve at a particular pressure-dependent optimum voltage $U_0(\Delta \Phi_r)$. This occurs at a voltage when the eccentricity of the lens profile matches with the refractive index ratio of the lens fluid to that of ambient silicon oil medium. As the voltage is increased further, the lens shape again departs from the perfect lens, thereby producing aspherical lenses of inferior optical quality. Figure 5.5b) represents the MTF plot of an aspherical lens corresponding to an initial backpressure of 68 Pa at varying values of voltage. Figure 5.5c) depicts the MTF curves of perfect lenses for different values of initial hydrostatic pressures. As is evident from the plot, the curves approximately fall on the diffraction-limited MTF indicating ideal lens behaviour, signifying superior optical quality.
Fig. 5.5. a) MTF versus angular frequency for four different values of hydrostatic pressure under zero voltage: 50 Pa (red), 56 Pa (blue), 68 Pa (orange), and 77 Pa (green). The black curve depicts diffraction-limited MTF. b) MTF versus angular frequency as voltage is applied at 0 kV (red), 1.32 kV (blue), 1.95 kV (orange), 2.12 kV (green), and 2.18 kV (pink) for ΔPh = 68 Pa. c) MTF curves of perfect lenses corresponding to four different values of ΔPh: 50 Pa (red), 56 Pa (blue), 68 Pa (orange), and 77 Pa (green). The inset shows the enlarged view of a section (black box) of superimposed MTF curves.

Other metrics with which to judge the optical quality employ spot diagram, Strehl’s ratio, and peak-to-valley (P–V) and RMS wavefront values. Spot diagram depicts the distribution of rays on the image plane. If the spot diagram lies entirely within the airy disc (black circles in Fig. 5.6), the system is said to be diffraction-limited. In our case, the airy disc diameter is 6.52 mrad. Figure 5.6a) illustrates the variation in RMS spot diameter and geometrical (GEO) spot diameter as hydrostatic pressure is increased from 50 Pa to 76 Pa. The corresponding values of spot diameters are tabulated in Table 2 (top). As is evident, the RMS and GEO spot diameters increase by increasing the pressure, eventually spanning outside the airy disc and thereby signifying degradation in image quality. The degeneration in optical quality is consistent with the degradation in resolution as discussed above regarding the MTF plot (see Fig. 5a.). Figure 5.6b) shows the spot diagram for the same conditions as the MTF plot in Fig. 5.5b). As expected, the diameter of the spot image decreases upon increasing the applied voltage at a fixed pressure and is finally contained within the airy disc at optimum voltage. Figure 5.6c) shows the spot diagrams of perfect lenses for different values of hydrostatic pressures. It is evident that, in all cases, the image spot diagram falls entirely within the airy disc, further corroborating the conclusion made in Fig. 5.5c) and highlighting the improved optical performance.
Fig. 5.6. a) Spot diagrams of spherical lenses under zero voltage at hydrostatic pressures of 50 Pa, 56 Pa, 68 Pa, and 77 Pa. The black circle represents airy disc. b) Spot diagrams of aspherical lenses corresponding to $\Delta P_h = 68\text{Pa}$ as the voltage is increased from 1.32 kV, 1.95 kV, and 2.12 kV to 2.18 kV. c) Spot diagrams of perfect aspherical lenses with $Z_{11} \approx 0$, corresponding to different values of $\Delta P_h$: 50 Pa, 56 Pa, 68 Pa, and 77 Pa.

The specific values of the GEO and RMS diameters of the spot images are summarized in Table 5.2 for a series of conditions. In Table 2, we also provide a series of other merit figures that are commonly used to quantify the quality of optical systems. Specifically, Strehl’s ratio gives the ratio of peak intensity of an aberrated system under consideration to the peak intensity of the diffraction-limited system as observed on the image plane from a point source. This varies between 0 and a perfect value of 1. Optical systems with Strehl’s ratios of $\geq 0.8$ are generally considered as excellent diffraction limited systems. Like the MTF and the spot diagrams, the Strehl’s ratio results also indicated that excellent optical performance can be achieved by applying the optimized voltage. Furthermore, we specify the P–V and RMS values of the wavefront aberration as calculated from the wavefront maps. As expected, the errors were reduced to somewhat smaller values at optimum voltages.
Table 5.2. Optical properties of a) Spherical lenses under zero voltage at hydrostatic pressures of 50 Pa, 56 Pa, 68 Pa and 77 Pa; b) Aspherical lenses corresponding to $\Delta P = 68$ Pa as voltage is applied from 1.32 kV, 1.95 kV, and 2.12 kV to 2.18 kV; and c) Perfect aspherical lenses under applied voltage corresponding to four different values of hydrostatic pressure: 50 Pa, 56 Pa, 68 Pa, and 77 Pa.

5.4 Conclusions

In this research, we have assessed the optical characteristics of the aspherical lens device reported earlier by Mishra et al. [2]. We formulated a numerical procedure to compute the performance parameters on Zemax, and we concluded that spherical aberration can be subsided and eliminated by the application of a voltage. This is realized by subjecting the liquid meniscus to an electric field. In another study, reported recently by Zhao et al. [24], it was experimentally demonstrated that for tunable elastomeric lenses of 3-mm clear aperture, considerable improvement in optical performance can be achieved over a focal length range of 6 mm to 12 mm. This was further confirmed by evaluating the MTF curves and RMS error. The Strehl’s ratio attained was 0.94, signifying diffraction-limited performance. In our case, the range of accessible focal lengths was between 1 mm and 14 mm. Also, as confirmed by various optical metrics, we were able to successfully achieve perfect lens configuration for different initial hydrostatic pressures by application of the voltage.
It is important to highlight the potential use of liquid aspherical lenses. Due to their tunable focal length and ability to reduce optical aberrations, liquid aspherical lenses offer potential applications in imaging. For example, while imaging a point object on a 170-micron coverslip through our lens device at 68 Pa under an applied voltage of 2.25 kV, by optimizing the distance between the coverslip and top glass plate, one can reduce the spherical aberration to less than 0.01 waves. Thus, the aberrations introduced in optical microscopy while imaging biological specimens can be compensated by electrical aberration control.

Standard objectives have a fixed numerical aperture and working distance. Aspherical lenses, on the other hand, come with the advantage of tunability. Variable numerical apertures and focal lengths can be achieved by effectively manipulating the hydrostatic pressure and voltage. By choosing fluids of different refractive indices and by optimizing the device design, one can further alter the tuning range of numerical apertures and focal lengths. Moreover, spherical aberration increases with numerical aperture. By applying an electric field and consequently inducing sufficient asphericity, however, it is possible to eliminate the pronounced spherical aberration encountered at higher numerical apertures.

Another advantage of electrically actuated liquid lenses is their operation speed. One can apply a voltage and correct the aberrations in few milliseconds. To improve the optical resolution, it would be desirable to increase the (geometric) aperture of the lens. This has the disadvantage that gravitational distortions of the lens shape, which scale quadratically with the aperture diameter become more important. It is possible, though, to compensate gravitational distortions by the electric field, too. The operation speed is expected to decrease as well, due to the possible excitation of oscillations of the lens surface. Experiments to evaluate the dynamic response and its consequences for the operation of larger lenses are ongoing.

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References


Chapter 6

Optical setup for wavefront characterization of lenses: Construction and Operation

Abstract

In this chapter, we describe the construction and working principle of the optical setup employed for the characterization of our optofluidic lens systems. We carry out the wavefront analysis of our lens system by using Shack Hartmann Wavefront Sensor (SHWS). The optical setup essentially consists of two arms: a reference arm and a measurement arm, each involving multiple optical elements. A step by step protocol is laid down for the alignment of each arm. Special attention is paid to the alignment of critical optical elements and accurate positioning of the lens device. The chapter is organized as follows: First, we discuss in detail the working principle of Shack Hartmann Wavefront Sensor (SHWS). Following this, we explain the construction and operating protocol of our optical setup. Finally, the optical system is validated by performing calibration measurements of the Zernike spherical aberration coefficients of two test lenses measured under zero defocus condition. The experimental values of coefficients are in excellent agreement with that evaluated from optical simulations performed on Zemax.
6.1 Working principle of Shack-Hartmann wavefront sensor (SHWS)

SHWS (supplier: Thorlabs)[1] is the most frequently used instrument for real-time wavefront characterization. It is employed for detecting optical aberrations and optimizing wavefronts for accentuating the performance of an optical system. It consists of a lenslet array of plano-convex microlenses made of fused silica. A CCD chip is mounted at a distance equal to the focal length of the lenslets. To ensure mechanical integrity of the device, the entire assembly is housed in a metal casing. Each lenslet array is denominated by its pitch and anti-reflection coating. Different lenslet arrays are required for different dedicated job specification in terms of their pitch (spatial resolution), focal length, wavefront sensitivity and dynamic range. The microlens array used in our experiments is WFS300-14AR. This represents an array of lens with pitch = 300microns and AR coating range of 400-900nm. The CCD camera offers flexibility in terms of resolution, maximum being 1280×1024 pixels = 1.3Megapixel. This corresponds to a camera size of 5.95×4.76mm. The working principle of SHWS is succinctly depicted in the fig. 6.1.

![Fig. 6.1. Detection of spots on CCD sensor. a) Regularly spaced spots due to planar wavefront falling on microlens array. b) Irregularly spaced spots due to distorted wavefront falling on microlens array. Figure taken from Thorlabs, Shack Hartmann wavefront sensor, SH tutorial.](image)

If a planar wavefront falls on a microlens array, it forms regularly spaced focal spots on the CCD (shown as red dots). These spots act as a reference and the distribution of spots on the CCD is called the reference spotfield. There are two kinds of reference wavefronts: planar wavefronts and spherical wavefronts. There is also a provision of internal reference, in case no reliable external reference is available. However, it is advisable that for accurate measurements, one resorts to actual reference wavefront based on the optical setup, rather than relying on the internal reference. The internal reference is always a planar wavefront. On the other hand, in case, the wavefront is distorted (Fig. 6.1b), after experiencing refraction from the microlenses, irregularly spaced spots are observed on the CCD. Hence, the very nature of the wavefront can be detected and further characterized by measuring the spot shifts with respect to the reference wavefronts. These local spot shifts are then used to calculate the local wavefront slope which is further integrated over 2D space to yield the 3D wavefront profile. Spot deviations are measured by the algorithms built in the software,
by calculating the centroid position of all the detectable spots on the CCD and then subtracting it from the reference spot coordinates. This is clearly explained in the fig. 6.2.

![Diagram showing detection of reference (green) and actual spot (red) positions on CCD due to the interaction of planar reference wavefront (green) and actual incoming wavefront (red) respectively with the microlens. Figure taken from Thorlabs, Shack Hartmann wavefront sensor, SH tutorial.](image)

If the incoming wavefront is tilted (in red), then spots are shifted in X and Y direction as observed on the CCD. The deviation angle $\alpha$ can be approximated as

$$\tan \alpha = \frac{\Delta x}{\Delta y} = \frac{\delta y}{f_{ml}}$$

If $W(x, y)$ is the incoming launched wavefront and $f_{ml}$ is the focal length of the microlens array (same as distance of CCD detector from the lenslet), the local slopes of the wavefront can be computed as

$$\frac{\partial}{\partial x} W(x, y) = \frac{\delta x}{f_{ml}}$$

$$\frac{\partial}{\partial y} W(x, y) = \frac{\delta y}{f_{ml}}$$

These spot deviations are further integrated to give three-dimensional wavefront. Care must be taken that the sampling spot density is sufficiently high i.e. there are adequate number of spots within the defined pupil on the CCD. For e.g. while illuminating lens (#32-478) aperture of 3.6mm diameter, we are using 480 number of spots to construct the corresponding wavefront. If the sampling density is low or if only few lenses in the lenslet are illuminated, the obtained wavefront would be inaccurate and result cannot be trusted.

All the stated information can be accessed in real time by simple graphical-user interface. The wavefront can then be decomposed into Zernike modes and the contribution of each
specific optical aberration like spherical aberration, coma, astigmatism etc. can be individually studied. The contribution of each particular aberration is specified by its Zernike coefficient. The higher the value of Zernike coefficient, the higher is the contribution of the particular aberration.

In order to measure the aberrations present in our lens system, we need the following:

a) a reference wavefront that passes directly through the optical system without the test lens and
b) a second wavefront that does pass through the test lens under consideration. The relative variation of the wavefront between these two beams as detected by SHWS is the wavefront distortion caused by the lens system. For achieving this, we first generate a (coherent) planar wavefront that (ideally) covers the full area of SHWS CCD chip. Further, we split the beam into two and pass the other half through our test system.

6.2 Optical setup: Construction

Fig. 6.3 Schematic of the optical setup. 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 M3 and M3’, passing sequentially through Microscope objective (OM1), 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.

This section describes the skeleton of the Optical setup. Fig. 6.3 illustrates the schematic of our optical setup. It essentially has two arms: Reference arm and Measurement arm. The
reference arm signifies a reference planar wavefront with respect to which liquid lens aberrations are measured, while the measurement arm comprises the lens device which is subjected to aberration measurement.

Fig. 6.4 depicts the construction of our optical setup. Incoming beam from an intensity tunable monochromatic laser source (Green laser, $\lambda = 534\text{nm}$; $P = 250\text{mW max.}$), is impinging on the mirror and is further directed through the assembly of lever-actuated iris diaphragms (ID25SS, $\phi 25\text{mm, ID, Thorlabs}$) into a Gaussian beam expander (BE 10M-A, 10X Magnification, BE, Thorlabs). The beam expander magnifies the beam diameter from 0.8mm to 8mm. Appropriately spaced ID’s are positioned for consistent optical alignment. All mirrors (ME2-P01 and ME05-P01, diameter $\phi = 1^\circ$ and $\phi = 1/2^\circ$ respectively, silver protected, 3.2mm thick) are housed in precision kinematic mirror mounts (KS2, $\phi 1^\circ$ and KS1, $\phi 1/2^\circ$), with three adjusters, all supplied from Thorlabs. Mirror mounts are elevated to the required height above the breadboard by optical posts (TR3, $\phi 1/2^\circ$, L = 3") held by post holders (PH4, standard black anodized, $\phi 1/2^\circ$, L = 4"), which in turn are mounted on the breadboard via mounting base (BA1S, 1"x2.3"x3/8"). In order to manipulate the beam size, an ID is positioned after the BE. The size of beam can be manually adjusted by changing the diameter of the aperture. The expanded beam of larger diameter is redirected into a non-polarizing beam splitter (BS013, 400 – 700nm, 50:50 intensity split ratio, BS1), where the expanded beam is split into two branches, each having half the intensity of the original one. The reference beam passes through BS1 straight and subsequently passes through a next non-polarizing beam splitter (BS013, 400 – 700nm, 50:50 intensity split ratio, BS2). The beam splitters are rigidly cased in a cube mounts (CM1-BS013). BS2 is attached to a tip-tilt mount (P100-P, Miniature platform optical mount, 2 knob adjuster, 1", Newport) and the entire assembly is screwed to a rotary stage (WV 100, supplier: Owis) via optical posts. The rotary stage is in turn attached to a X-Y translation stage (XYT1, XY stage with $\phi 1^\circ$, 13mm travel), screwed on the breadboard. A CCD camera (uEye, UI-1225LE-M-HQ, C1) is also placed behind BS2. C1 is required for the interferometric alignment of the light passing through the reference and the measurement arm. An optical shutter (OS1) is placed between BS1 and BS2 to block the beam from BS1. The beam then falls on the relay system, comprised of two bi-convex lenses (RL1 and RL2) of focal lengths $f_1 = 50\text{mm}$ and $f_2 = 100\text{mm}$, separated by a distance of $d = f_1 + f_2 = 150\text{mm}$. Each of the relay lenses, RL1 and RL2 is placed on an X-Y translation stage (RL1: MKT 40C miniature x-y stages, supplier: Owis and RL2: Miniature x-y stage, supplier: Elmekanic) mounted on post holder bases (BA2, 1"x4.5"x3/8"). The relay system arrangement, magnifies the beam size by a factor of two, ensuring 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 very beam then falls onto the CCD (5.75x4.76mm) of Shack-Hartmann wavefront sensor (WFS150-7AR, SHWS). The SHWS is mounted on a tip-tilt platform (KM100WFS, kinematic mount for wavefront sensor, KMWS) which in turn is attached to a X-Z translation stage. KMWS is provided with two adjusters for fine tip and tilt control. It is important to highlight another fundamental purpose, which the relay system serves. It is employed to ensure that beam size is sufficient to cover maximum possible area of CCD. This guarantees that a sufficient
number of lenslets on the SHWS are illuminated to achieve an accurate measurement. Construction and working of SHWS is explained in detail in section 1 of this chapter.

Fig. 6.4. Laboratory picture of the optical setup employed for wavefront characterization of liquid lenses. Orange arrow shows the laser. b) Enlarged picture of a section of measurement arm showing microscopic objective (marked in red) mounted on linear translation stage, LTS-300 (marked in light blue) and lens device mount, LMI (marked in dark green) underneath the objective. Yellow arrow shows the objective mount, OM1.

The measurement arm constitutes the other beam emanating from BS1, further directed by a 45° mirror (M1) through a vertically stationed construction rails (XT66-500, 66mm construction rail, L = 500mm and XT66-200, 66mm construction rail, L = 200mm), perpendicular to the breadboard. This beam can be blocked by a flipper optical mount (Model: 9891, 1”, Newport, FOM) positioned between M1 and FOM. XT66-200 and XT66-500 are dovetailed by a rail joiner (XT 66J, Rail joiner for 66mm rails). The large beam path of 700mm ensures minimum play and expedites optical alignment. The beam is then guided horizontally along XT66-500 construction rails via two mirrors (M3 and M3’). It then falls on the back aperture of a microscope objective (Mitutoya, M Plan Apo, 10X/NA = 0.28), an infinitely corrected apochromat, threaded to an objective mount (KM100R, Kinematic mirror mount for microscope objective, OM1), fastened to a 3-axis microblock stage (MBT616/M, with differential adjusters). MBT616/M is in turn attached to a motorized linear translation stage LTS-300 (300mm translation stage with stepper motor, Integrated controller, travel range: 300mm). It offers various possibilities of mounting different kinds of optomechanics depending on the specific requirements. The translation stage is rigidly attached to the vertical construction rail (CS1). The movement of the objective is precisely controlled by APT, an application software provided along with LTS-300. GUI of APT enables smooth and metered longitudinal translation of the objective. The position of the objective can be determined from the APT interface. It gives flexibility to monitor and control the speed, acceleration and the step size of the objective.
Finally, the lens that is to be tested is mounted on a kinematic mount (KM100, Threaded kinematic mount, 1°, LM1), enabled with tip and tilt. It is also connected to an X-Z stage, composed by clamping two linear stages together (LT45, precision linear stage, travel range 85mm, Supplier: Owis). Four circular notches are drilled on the four corners of LM1 in order to smoothly accept the lens device. The device construction and its functioning mechanism is explained in detail in the next chapter. The lens device in current design is operated in a horizontal configuration. LM1 is in turn attached to the manually assembled translatable mount LM2. LM2 is composed of a Z-axis bracket for LTS-300 stage mounted on single axis translation linear stage (PT1, travel range: 1", engraved graduations: 10µm). This arrangement offers considerable flexibility in operation, which is crucial for successful alignment of the setup and for the subsequent characterization of the optofluidics lens device. The test lens, thus, can be positioned axisymmetrically with respect to incoming light beam. 45° mirror (M2) is fixed on the 3-axis microblock stage (MBT616/M, with differential adjusters) to re-orient the beam coming from the device back to horizontal plane which subsequently falls on BS2. MBT616/M provides both coarse and fine adjustments offering a travel range of 4mm and 300µm and resolution of 500µm/rev and 50µm/rev respectively. The measurement beam from BS2 then impinges on the relay lens system, ultimately falling on the CCD of SHWS.

In order to prevent the effect of any stray light, experiments are conducted under minimum ambient light conditions. Critical optical elements, prone to misalignment, due to human negligence, are safely housed under protective shields. The optical bench is covered by plastic curtains from all sides to guard against any incoming dust. The entire optical unit is operated under pure air circulation unit which continuously supplies clean and dry air. Black aluminium fabric (BLF12, Matte black aluminium foil) is used to preclude any unwanted reflections.

6.3 Optical setup: Working procedures

In this section, we shall discuss the step by step procedure to functionally operate our optical setup. We shall also explain the alignment of optical elements and finally shall report the Zernike aberration coefficients of a test lens as recorded by SHWS.

a. Alignment of objective mount: This step is required to ensure that the vertical part of measurement arm does not translate laterally as translation stage moves up and down. A mirror (M4) of appropriate size is placed in the objective mount OM1 and a second mirror is positioned at X1 as shown in the fig. 6.5. The interference of back reflected beam from M4 and reference beam from BS1 is observed on the camera positioned at X2. OM1 is adjusted such that two beams form concentric interference fringes as OM1 is translated along the linear stage, LTS-300. This ensures that movement of OM1 is strictly in line with the orientation of LTS-300. This is particularly important as LTS-300 will not be perfectly aligned with the vertically mounted construction rail (XT66-500).
Fig. 6.5. a) M4 (red) signifies the position of mirror in an objective mount (At this stage, objective is not mounted). b) X1 (red) and X2 (green) denote the positions of mirror and camera respectively, temporarily taken away for the image.

b. Alignment of BS2 beam splitter: Next, two cameras are positioned in the vicinity of BS2, at positions X3 and X4 as shown in the fig. 6.6., perpendicular to each other, such that the reference beams and measurement beams interfere are well aligned in both direction and produce well-defined concentric interference patterns. BS2 is optimally positioned by observing the two interference fringes and is finely tuned till the two fringe patterns, observed on two different cameras, are concentric simultaneously. This is realized by manually adjusting the tip-tilt (P100-P) and precisely rotating it via graduated rotary stage (WV 100). X-Y orientation is controlled by X-Y translation stage (XYT1).

Fig. 6.6. X3 (green) and X4 (green) denote the positions of two cameras for observing interference fringes. BS2 is considered perfectly positioned when the fringe patterns noted on the two cameras are simultaneously concentric.
c. **Alignment of microscopic objective:** This is executed by flapping up the flipper optical mount (FOM), thereby restricting the measurement beam coming from BS1, placing a mirror at position X3 as depicted in the fig. 6.7, stationing a camera at a position X4 and linearly moving the objective along the translation stage, LTS-300. The objective is accurately aligned by observing the interference fringes formed due to the interaction of two beams, one from the reference beam coming from BS2 and other from the back reflection of the front lens of the objective.

![Fig. 6.7](image)

*Fig. 6.7. X3 (red) and X4 (green) denote the positions of mirror and cameras respectively. Mirror is used to reflect the reference beam to front lens of objective which is then reflected back on to the camera stationed at X4.*

The figure below sums up the coordinates of cameras and mirrors as discussed above.

![Fig. 6.8](image)

*Fig. 6.8. Illustrates the position of various cameras and mirrors used in step (1), (2) and (3) for aligning the objective mount, BS2 and the objective.*
d. **Interferometric alignment of the test lens (optofluidics device)**: This step involves placing the lens device on the LM1 mount (highlighted in light green) and placing the two cameras at positions $X_3$ and $X_4$ as shown in the fig. 6.9. Further, reference and measurement beams are used to interferometrically aligned the device. The LM1 mount, equipped with tip-tilt facility, is adjusted to fine tune the device position such that lens aperture of the device remains axisymmetric to the beam coming from the front lens of the objective. This is confirmed by the fact that centre of concentric fringes remains stationary, as observed on the camera, while objective is linearly actuated along LTS-300. The interferometry enables us to position the lens device with precision and accuracy, as the objective translates along the linear stage, LTS-300.

![Fig. 6.9. a) Lens mount, LM1 (marked in light green) for accepting the lens device. $X_3$ and $X_4$ denote the positions cameras for interferometric alignment of the test lens. b) Enlarged view of the lens mount.](image)

e. **Positioning the relay lenses and SHWS**: Relay lenses (RS), RL1 and RL2, with their mounting platforms are screwed on the breadboard and are adjusted such that the distance between the lenses is equal to the sum of their focal lengths. This arrangement magnifies the beam size by a factor of two. Following this, we finally attach the SHWS to the breadboard and manoeuvre its position such that tip and tilt are nullified. Relay system and SHWS are depicted in the fig. 6.10. The tip and tilt can be read from the SHWS software. The software also displays Radius of curvature of the wavefront (RoC). The reference wavefront is considered planar for RoC > 10m. This is further corroborated by Zernike defocus aberration (Z5). For parallel wavefront, this corresponds to $Z5 < 0.01$ waves.
f. **Recording the Zernike aberration coefficients:** The objective is translated along the LTS-300 such that the distance between the objective and lens device is equal to sum of the working distance of the objective and focal length of the lens. This ensures that the beam emanating from the device has minimum defocus aberration. The measurement beam contains the optical information about the lens device which can be read by the application software provided with the SHWS.

g. **Estimation of focal length:** Focal length of lens device at zero voltage, can be readily calculated by measuring the initial distance between the lens device and microscopic objective under zero defocus condition and then subtracting from it the working distance of the objective. This initial position of the objective is recorded on scale by the application software APT. Subsequently, as the focal length of the adaptive optofluidic lens is changed by applying a voltage, the distance between the lens device and objective has to be re-adjusted to ensure zero defocus condition. The position of the objective is again read by the scale attached to LTS-300. This procedure has to be repeated every time any of the control voltages (or pressures) on the adaptive lens is varied. Thus, by making use of the recorded position of the objective at zero voltages and at finite voltage, one can determine the focal length of the lens device.

### 6.4 Experiments vs. Simulations

In order to validate the experimental accuracy of our optical setup, we calculated the spherical aberration of the two plano-convex test lenses denominated as: #47-381 (6.00mm diameter, 48mm focal length, N-BK7, NA = 0.06) and #32-478 (25.00mm diameter, 50mm focal length, N-BK7, NA = 0.25). It is important to note that numerical aperture of microscopic objective (NA = 0.28) always has to be greater than the one of the test lenses under consideration. This is to ensure that the full lens clear aperture can be illuminated under zero defocus aberration. Fig 6.11 represents the variation of Zernike spherical aberration coefficient (Z13) against the illumination diameter of the lens. The optical setup is simulated on Zemax, as explained in...
detail in chapter 5. The Z13 coefficient is evaluated under zero defocus condition. Afocal mode is invoked in Zemax to ensure reference wavefront is planar. Monochromatic light of \( \lambda = 534 \text{nm} \) is used to illuminate the lens aperture. As explained already in Chapter 5, we quantify the wavefront distortions in units of “waves”, which signifies phase difference. It is evident from the plots that experimental values are in good agreement with the performed simulations. In case of lens #47-381, a discrepancy is observed between the experiment and simulation, when the beam diameter is 2.6mm. This inaccuracy can be attributed to the insufficient number of microlenses being utilized in the evaluation of Z13 Zernike coefficient as only a fraction of lens clear aperture is illuminated for an aperture diameter of 2.6mm. Secondly, it is also observed that spherical aberration increases as the diameter of illuminated lens aperture is increased. This is consistent with the fact that spherical aberration accentuates as the marginal focal length decreases with the increase in beam diameter, while paraxial focal length remains the same.

![Graph](image)

**Fig. 6.11.** Variation of Zernike spherical aberration, Z13 vs. illumination diameter of lens aperture of two plano-convex test lenses: a) #47-381 and #32-478 (see text for details). Red squares denote experiments while black square represent Zemax simulations.

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Chapter 7

Design and wavefront characterization of optofluidic lens device

Abstract
This chapter discusses the wavefront characterization of our aspherical lens device on an optical setup as described in chapter 6. We delineate the fabrication and operational mechanism of the lens device. Here, unlike in chapter 4, we employ electrowetting rather than hydrostatic pressure to regulate the initial backpressure. The device is actuated by two control parameters: Electrowetting voltage and Lens voltage (This is defined as the voltage applied between aperture plate and top electrode). Hence, the entire device is operated electrically. We, therefore, in this chapter introduce the new design of an all electrically controlled adaptive lens that allows for manipulating the back focal length and asphericity of the optofluidic lens. We further provide an SHWS-based characterization of the lens aberration and report the Zernike spherical aberration (Z13th coefficient) and back focal length as recorded by application of pure electrowetting voltage (EW-Voltage) from 0V to 70V with a step size of 10V, under zero lens voltage. We observe that focal length and spherical aberration are tunable as we apply the voltage back and forth with negligible hysteresis. Following this, we apply the lens voltage at each specific EW-Voltage. We are able to reduce the spherical aberration from 0.06waves to 0.003waves by application of the lens voltage. Perfect aspherical lenses with zero values of Z13 are obtained by deforming the initial lens meniscus into aspherical configurations by application of lens voltage.
7.1 Introduction

Liquid lenses have been a subject of much interest due to their remarkable properties and advantages they offer over regular solid lenses. One of their salient feature is the focussing ability as their configuration can be tuned by employing different pressure mechanisms. Geometrical properties of liquid lenses like focal length and optical power have been widely investigated and documented[1-8], as also reviewed in detail in chapter 2. In chapter 4 of this thesis (see also Mishra et. al.[9]), we demonstrated that longitudinal spherical aberration (LSA) can be mitigated and eventually eliminated by application of the voltage on a spherical drop pinned along the aperture. Geometrical ray-tracing routines were employed to calculate focal lengths and LSAs of the various lens profiles at different voltages (see Chapter 4). However, a deeper analysis is required beyond the domain of geometrical optics to understand the wavefront nature of liquid lens optics. Therefore, it is imperative to judge the optical performance of any optofluidic system in the real world environment. This calls for a more accurate detection and quantification of optical aberrations. Traditionally, interferometers were used for computing optical aberrations. Interferometers capture interferograms which were then subjected to post experimental analysis for numerical determination of each of the optical aberration. However, with the advent of new technology, novel experimental methods evolved, replacing interferometers with more advanced and sophisticated equipments. Wavefront sensing, in this context, has emerged as the most ubiquitous technique adopted in research and industrial applications to gauge the resolution of optical systems of all sorts, including adaptive liquid lenses. The technique can be employed under both static and dynamic conditions and comes with an advantage of real time analysis. It also gives a quantitative measure of the optical aberrations present in any lens system. Additionally, it provides us the real time feedback of optical aberrations and an insight to judge which aberrations are to be subsided for improving the overall imaging potential of the lens. These benefits make wavefront sensing the most widely accepted tool for optical characterization of lenses. The Shack Hartmann wavefront sensor (SHWS) is the most widely used instrument employed in wavefront sensing for capturing the wavefronts. Construction and working of SHWS is explained in detail in chapter 6. Large amount of literature is available on the subsequent decomposition of wavefronts into Zernike modes, thereby evaluating each specific aberration separately[10] (see also Chapter 2). As reported by Li et. al.[11] it can be used to capture three dimensional surface profiles of liquid lenses. For cylindrically symmetric lenses, the profiles are then fitted to conic sections in order to extract their geometrical properties like radius of curvature and conic constant. Finally, the geometrical parameters are imported to Zemax to construct a simulation model in order to estimate the optical properties of liquid lenses. Amongst many other applications, a Shack Hartmann Wavefront Sensor (SHWS) was also used to measure the aberrations present in solid fused silica microlenses[12]. Tung et. al.[13] presented a detailed account of measurement of optical properties of dielectric liquid lens in both steady and transient stage, enlisting different primary aberrations. Astigmatic properties of elastomeric lenses subjected to mechanical pressure strain have also been experimentally investigated under zero defocus condition[14]. Lima et. al.[15] carried out numerical simulations on Zemax to understand the astigmatic behaviour of electrically tunable liquid lenses under the effect of stripe electrode and estimated the
pertinent Zernike astigmatic coefficients. Mishra and Mugele[16] numerically computed the Zernike spherical aberration coefficients by applying voltage between the planar ITO electrode and deformable liquid lens drop, trapped in an aperture. It was observed that at a specific voltage, depending on the lens and ambient fluid properties and on device design, when eccentricity of the aspherical lens profile matches the refractive index ratio of the lens fluid to that of an ambient medium, spherical aberration is eliminated. Such an observation was further corroborated by the superimposition of MTF (Modulation transfer function) curves of the optical system on the diffraction limited perfect lens curve.

Here, we use electrowetting to control the initial backpressure of lens meniscus instead of hydrostatic pressure employed in chapter 4. The hydrostatic head makes the entire device operation more cumbersome and renders it prone to external disturbances. This calls for the fabrication of more compact and robust aspherical lens device, operated entirely by electrical control and resistant to external shocks. In our current device design, it is not possible to capture the side view images and hence meniscus surface shapes are no longer accessible. However, our objective of device characterization is served by employing SHWS. Moreover, SHWS provides quantitative measurements of aberrations present in our lens device system. As described earlier, SHWS offers real time feedback based on wavefront analysis, beyond simple geometrical ray-tracing.

7.2 Aspherical lens: Device Fabrication

In this section, we will describe the construction and working of a robust and compact aspherical lens device. The device works by regulating the backpressure via electrowetting, instead of hydrostatic pressure as described in chapter 4. However, the usage of top electrode for inducing asphericity is retained. In nutshell, the entire device operation is controlled electrically, devoid of any other kind of hydrostatic pressure stimulus. Each plate is denominated by a specific plate number. The device consists of three plates: bottom plate (1), aperture plate (2) and top plate (3), each of dimension 5×5cm², see Figure 7.1. A liquid drop is sandwiched between the bottom plate (1) and aperture plate (2). The bottom plate (1) consists of teflon coated ITO electrode, capable of electrowetting modulation. Hence, by applying voltage between bottom plate (1) (2.7×2.7cm²) and aperture plate (2) (2.7×2.7cm²), one can manipulate the curvature of the liquid lens droplet entrapped in the aperture. Increasing the voltage, decreases the contact angle of the sandwiched drop on the bottom substrate, thereby decreasing the curvature of the liquid droplet pinned along the aperture. Additionally, non-homogenous electric field is induced by applying voltage between the top electrode (3) (2.7×2.7cm²) and aperture plate (2). Teflon coated substrates were tested for electrowetting reversibility by creating a drop of aqueous salt solution under silicon oil. We were able to tune the initial contact of 165° at zero voltage to 65° at 120V, back and forth, with extremely low contact angle hysteresis of less than 8°. Distance between the bottom plate (1) and aperture plate (2) is 1.5mm, while that between aperture plate (2) and top electrode is 2.5mm. Such spacing is chosen by considering the range of applied voltages over which electrowetting can be performed and voltage requirements for producing aspherical shapes corresponding to perfect lenses. Bottom (1) and top plates (3) are provided with a square notch of size 2.7×2.7cm² and 0.5mm thick for attaching the ITO electrodes, with thickness of aperture plate (2) being 170 microns. Backing plates (4 and 5),
5×5cm², made of stainless steel, are provided to ensure rigidity to the entire device, safeguarding the device from any external shock and disturbance. Aqueous salt solution is used in the drop phase (Refractive index: 1.46) and silicon oil (Refractive index: 1.40) as an ambient fluid. Multiple holes are symmetrically drilled in the aperture plate (2), around the central aperture of size 1mm (in diameter), for enabling the smooth exchange of fluids between the top chamber comprising, top (3) and aperture plates (2) and bottom chamber, consisting of aperture plate (2) and bottom plate (1). Aperture plate (2) is hydrophobized by dipping it in 1% thiol solution of ethanol for 24hrs. A triangular cut of size 8.6mm (distance measured from the corner of the plate) is also provided at the one end of aperture plate for making electrical connections. Each plate is suitably provided with a rectangular slot of size 2mm×200microns for inserting copper foils. Bottom substrate (1) is soaked in silicon oil overnight to enable efficient depinning of contact line. O-rings (ID:40mm and thickness:1mm) are appropriately provided so that the device is hermetically sealed and is leak proof, independent of any orientation. Each plate, including backing plates is machined with four holes (ID:2.9mm), drilled at each of the four corners. The device is operated by first placing the teflon coated ITO electrode in the square notch of the bottom plate, followed by screwing together aperture plate (2) and bottom plate (1). Aqueous salt solution is carefully injected into the orifice of the aperture plate (2) for creating the lens droplet. This assembly is then gently placed inside silicon oil bath. Next, we place the top plate with the attached ITO electrode and then screw the entire assembly along with the backing plates (4 and 5). Performing the entire operation inside silicon oil bath precludes entrapment of any unwanted air bubble. The stacked configuration also ensures perfect alignment. Lens droplet is perfectly pinned by hydrophobic-hydrophilic contact line along the aperture.

Fig. 7.1.a) Exploded view of the device. b) Assembled lens device.

7.3 Results

The step by step procedure for carrying out the Shack-Hartmann wavefront measurement is explained in the chapter 6. In a nutshell, the operation involves aligning the reference arm, followed by the alignment of reference wavefront by Shack-Hartmann wavefront sensor
(SHWS), positioning the lens device on the lens mount and subsequently translating the microscopic objective along the linear translation stage (LTS-300) such that the distance between the objective and lens device is equal to the sum of their working distance and back focal length respectively. All measurements are performed under zero defocus conditions. As stated in chapter 6, aberrations are measured with respect to planar wavefront.

The experiments are conducted under silicon oil ambience (Refractive index: 1.40) with aqueous salt solution as the lens fluid (refractive index: 1.461). Device fabrication and liquid filling procedure is described in detail in the previous section. Initially, the lens voltage is set to zero. Initial curvature of lens meniscus is controlled by electrowetting, while asphericity is induced by applying the voltage between aperture plate and top electrode. Electrowetting (EW) modulates the contact angle of the lens on the teflon coated bottom substrate. As EW-voltage is applied, contact angle decreases, consequently curvature of the lens decreases and its focal length increases. As the EW-voltage is released, drop regains its original shape, thereby attaining the original focal length at a specified voltage. This is evident from the fig. 7.2a. as the voltage is applied from 0V to 70V in the upward cycle and is then decreased from 70V to 0V in the backward cycle. The focal lengths at each specific EW-voltage superimpose on each other during upward and backward cycle respectively with minimum hysteresis, demonstrating excellent reversibility. Similar trends are also observed for Zernike spherical aberration coefficient (Z13). At zero EW-voltage, due to high curvature, lens device with 2mm lens aperture has a considerable spherical aberration of 0.06waves. As an EW-voltage is applied, lens curvature reduces, thereby resulting into reduced values of Zernike spherical aberration coefficient (Z13) as illustrated in the fig. 7.2b.

**Fig.7.2.** Variation of **a)** focal length (squares) vs. Electrowetting voltage and **b)** Zernike spherical aberration (circles) vs. Electrowetting voltage, as the voltage is tuned back and forth from 0V to 70V. Red curve denotes the forward cycle as electrowetting voltage is applied and black curve signifies backward cycle as electrowetting voltage is released.

Initially, as lens voltage is set to zero, lens meniscus assumes a spherical shape. As lens voltage is switched on, meniscus translates from spherical morphology to aspherical configurations. Under zero EW-voltage, Zernike spherical aberration (Z13) decreases from
waves to 0.003 waves as lens voltage is applied from 0V to 1400V. Subjecting the
liquid-liquid interface to electrowetting, under zero lens voltage, contact angle of liquid-
liquid interface on the bottom teflon coated substrate decreases. However, liquid lens
meniscus retains its spherical shape as electrowetting acts only along the contact line. $Z_{13}$
coefficient is recorded for different lens voltages at each specific EW-voltage. As evident
from fig. 7.3, $Z_{13}$ falls sharply as lens voltage is applied at each specific EW-voltage. The
lens profiles corresponding to zero values of $Z_{13}$ signify perfect lenses with completely
suppressed spherical aberration. The trends are consistent with the results reported in
chapter 4.

![Fig.7.3](image)

**Fig.7.3.** Variation of **a)** focal length (squares) vs. lens voltage and **b)** Zernike spherical
aberration (circles) vs. lens voltage, as the voltage is applied between the aperture plate
and top electrode. EW-voltages (in squares) are denominated as: 0V(black), 10V(red),
20V(blue), 30V(pink), 40V(green), 50V(dark blue), 60V(purple), 70V(orange).

### 7.4 Conclusions

In this work, we have presented the construction and working of an optofluidic lens device.
We have shown that it is adaptive in nature and has the ability to capture high resolution
images of the specimens located at varying distances as demonstrated by its tunability in
focal length. This is achieved by simply transmuting the lens morphology by application of
EW-voltage or lens voltage or by regulating both the voltages simultaneously. The
application of lens voltage induces asphericity and gives us an additional leverage of
aberration control, apart from altering the focal length. Spherical aberration can be
suppressed for different initial meniscus curvatures by the application of finite lens voltage.
Also, we can simultaneously modulate EW-voltage and lens voltage, thereby manipulating
the lens meniscus for achieving varying focal lengths under minimum spherical aberration
at each particular focal length. Lens switchability is fast with a response time of less than a
second. By exchanging the top planar electrode with stripe electrode, one can produce
tunable astigmatic lens as numerically demonstrated by Lima et. al.[15]. Recently, Lima et.
al. computed the optical performance of universal liquid lens device on Zemax capable of
generating tunable optical aberrations by using a composite electrode composed of 100
square grid electrodes. Hence, by replacing the top planar electrode with such a grid
electrode, it is possible to tune different optical aberrations. The device, therefore, is versatile and can be used for generating arbitrary meniscus shapes for compensating various primary aberrations.

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References

Chapter 8

Conclusions and Outlook

8.1 Conclusions
In this thesis, we have focussed particularly on the fabrication and operation of electrically tunable optofluidic lenses. Electrowetting, has been one of the most promising industrial technique for manufacturing robust and reliable liquid lenses. However, so far the objective of industrial manufacturing of liquid lenses is essentially limited to the reversible modulation of focal length. The use of liquid lenses in correcting optical aberrations is still in the nascent stage and the particular domain is very much unexplored. This thesis is an effort in that direction. As reported in the literature in chapter 2, there has been a considerable effort to produce optically superior liquid lenses. In this thesis, we have addressed the problem by employing electric field as a driving stimulus for producing liquid lenses with tunable focal lengths and exploring their ability for compensating spherical aberration. It is illustrated, both by experiments and numerical analysis that aspherical liquid lenses generated by application of electric field are capable of suppressing spherical aberration with simultaneous tunability of focal length.

8.2 Outlook
The optical performance of our device can be further improved by adjusting certain design parameters. Lens device can be optimized to yield faster switching times of order of milliseconds for fast scanning applications. This calls for in-depth understanding of dynamics of liquid-liquid system. In order to improve the optical resolution of our lens device, it will be imperative to enlarge the lens numerical aperture. However, increasing the aperture diameter would enhance the effect of gravity, distorting the lens meniscus from spherical profile under zero lens voltage. This requires careful selection of density matched liquids so that device can operated in any orientation. Moreover, initial spherical aberration of lens device under zero lens voltage would substantially aggravate. However, under the application of lens voltage this can be mitigated by transforming the initial spherical lens meniscus into aspherical lens profile. Enhancing the aperture size would work to our advantage by severely reducing the voltage requirements due to reduced Laplace pressure. The high voltage requirements of order of kVs can be further reduced by optimizing the distance between aperture plate and top electrode. Moreover, the current device is passive and calls for active control. It can be made more responsive by an active feedback control for automated wavefront correction as voltage is applied.

Industrial manufacturers have overcome some of the listed deficiencies by fabricating robust and stable devices with longer shelf life. Companies like Liquavista, Optotune,
Cognex and Varioptic have successfully designed and fabricated EW-tunable variable focus liquid lenses with fast response time and high optical power. Optotune, for example, has introduced a series of electrically and mechanically actuated liquid lenses with adjustable focus. Cognex manufactured electrowetting lens for reading barcodes. Recently, Varioptic has released focus tunable liquid lenses with additional salient feature of correcting astigmatism. Such lenses can be of paramount importance in ophthalmic applications. However, as pointed out earlier in conclusion, the goal of using liquid lenses is still very much limited to focus tunability.

The use of lens device can be extended to multitude number of mundane applications ranging from aspherical lenses for suppressing spherical aberration to electrically tunable astigmatic lens by making use of the stripe electrode. It can be employed for mitigating ocular astigmatism in ophthalmic applications. This approach has been adopted recently in the Physics of Complex Fluids (PCF) group by Lima et.al.[1] for fabricating liquid astigmatic lenses using stripe electrode. The fluidic simulation model was then imported to Zemax to measure the degree of astigmatism by evaluating corresponding Zernike coefficient, under zero defocus condition.

The proposed lens device in this thesis is adaptable and versatile and can cater to the different industrial applications. The top electrode can be easily exchanged with a composite electrode composed of multiple individually addressable striped electrodes. This offers the leverage of actuating the lens meniscus into different topographical shapes as per the requirement. For example, applying voltage to all the stripes simultaneously, liquid-liquid interface can be tuned into an aspherical lens. Similarly, astigmatic lens can be produced by only stimulating the central electrode stripe and leaving the rest electrically inert. By activating only the off-centered electrodes one can fabricate comatic lenses. Moreover, the degree of coma induced can be controlled by the distance of activated decentred electrode from the central stripe electrode. We can also explore the possibility of enhancing the field of view without compromising the lens quality by applying voltage to the decentred electrodes. Additionally, myriad number of other meniscus profiles can also be produced by changing the electrode pitch. Hence, the slight alterations in device design can fetch meniscus shapes with different optical properties each suited for specific requirements. Employing arbitrary electrode geometries offers the possibility of aberration control in applications demanding higher optical quality. This would require a more robust design and fabrication procedures. Unlike flat single electrode, more sophisticated electrical circuitry is required for selective actuation of electrodes. Another aspect is the choice of appropriate liquids which would enable long term stable operation without damaging the substrates and mechanical parts of device. One fit choice for ensuring such reliability and longer shelf life of lens device can be the optical liquids from the Cargille Labs. Such liquids are quality checked and custom made for optical applications. The lens device can also be integrated into microscopic objective for applications in microscopy. Dynamics focus VZM lens is one such composite optical system, designed and manufactured by Edmund optics offering zooming capabilities from 0.65X to 4.6X with adjustable focus. It will be interesting to study the optical performance of our lens device in combination with a microscopic objective as our device comes with an ancillary leverage of tuning asphericity.
offering more flexibility in device operation. More research and optimization is required to develop robust optofluidic lens devices with innovative design.

References

Summary

The objective of this research is to fabricate and characterize an adaptive optofluidic lens device with aberration control. In this work, an electric field is employed as a driving tool to manipulate the liquid-liquid interface for suppressing spherical aberration by using a single flat unstructured electrode. The equilibrium lens meniscus profiles are determined by the balance of Laplace pressure and Maxwell stress. It involves understanding the response of a liquid drop under the influence of electric field and further discerning the optimum drop shapes which would yield the best optical performance. First, lenses are characterized by capturing the side view images of meniscus profiles and calculating the Longitudinal spherical aberration (LSA) by geometrical ray tracing. Subsequently, ray tracing analysis of optically measured lens profiles is performed on Zemax for numerically computing the Zernike spherical aberration (ZSA) coefficients and other standard optical metrics. Next, all-electrically controlled optofluidic lens device with EW-based pressure controller and electrically adjustable lens shape is designed and fabricated. The optical performance of lens device is evaluated by experimentally measuring the ZSA coefficients by using a Shack-Hartmann wavefront sensor (SHWS). The measured range of EW-tunability of focal length and spherical aberration is 10.1mm to 26.76mm and 0.059waves to 0.003waves respectively.

Chapter 1 is an introduction to optofluidic lenses. It discusses the advantages pertaining to the use of liquid lenses over customized solid lenses, simultaneously highlighting the challenges and limitations posed by liquid lens technology. It subsequently explains the motivation behind this particular research and reasons for the use of electric fields as a driving stimulus for liquid lenses as compared to other driving mechanisms.

Chapter 2 reviews the recent developments and evolution of liquid lens technology. It enumerates the various mechanisms to tune the shape of liquid-liquid interfaces for manufacturing adaptive liquid lenses, particularly focussing on the application of electric field. It discusses the advantages and drawbacks of each particular mechanism. Subsequently, lenses are classified in two categories on the basis of their shapes: Spherical and Non-spherical. Non-spherical lenses are further classified into aspherical and cylindrical lenses.

Chapter 3 enlists the various tools and methods employed in characterization of lenses. It discusses the standard laboratory techniques regularly employed in wavefront characterization of lenses. It further describes the mathematical representation of an optical wavefront and its decomposition into an orthogonal set of Zernike polynomials with each polynomial representing a particular kind of aberration. Other important optical metrics like Modulation transfer function(MTF), Strehl’s ratio, Peak to valley (P-V) and Root mean square (RMS) wavefront error signifying optical performance of lenses is also discussed in
detail. It further entails a discussion of the optical simulation platform Zemax and modelling of optofluidic systems on the same.

In chapter 4, we constructed an optofluidic lens and characterized it by ray tracing in Matlab, employing geometrical optics. It is shown that LSA can be reduced and eventually eliminated as the lens acquires a hyperbolic profile, under the influence of electric field. This occurs when the eccentricity of the lens profile matches the refractive index ratio of the lens fluid to that of ambient medium. We experimentally demonstrated that the liquid-liquid interface can be electrostatically modulated into a tunable and adaptive fluidic aspherical lens by applying electric field to a drop entrapped in an aperture. This is further confirmed by imaging a square grid through an aspherical liquid lens.

In chapter 5, we modelled and assessed the optical performance of liquid lenses on Zemax. The lenses are characterized on the basis of wavefront aberrations by evaluating ZSA coefficients and estimating other standard optical metrics like MTF, Strehl’s ratio etc. The simulations corroborate the experimental outcomes of chapter 4. It is further confirmed by numerical analysis that our lens device offers superior optical performance and improved image quality as compared to standard spherical lenses.

Chapter 6 describes the construction and working protocol of the optical setup. We had built the necessary optical setup needed for the wavefront characterization of lenses by SHWS and studied the optical properties by experimentally calculating the ZSA coefficients under zero defocus condition. The entire optical setup is calibrated and its reliability is confirmed by measuring ZSA coefficients of two test lenses and by comparing the measured experimental values with the simulations from Zemax.

In order to further validate our claim, we designed and fabricated a more robust, portable and compact fluidic lens device. Chapter 7 describes the fabrication and working of an optofluidic lens device. Unlike the handmade device of chapter 4, in this upgraded version of the liquid lens device, curvature at zero voltage (Voltage applied between aperture plate and top electrode) is controlled by electrowetting rather than hydrostatic pressure. We further demonstrated the electrowetting reversibility of the lens by tuning the electrowetting voltage back and forth. Similar reversible behaviour is also observed for the ZSA coefficients. We experimentally illustrated the complete suppression of spherical aberration by applying a voltage between the aperture plate and top electrode.
Samenvatting

Het doel van dit onderzoek is het maken en karakteriseren van een optofluïdische lens waarvan de lenseigenschappen controleerbaar zijn. In dit werk wordt m.b.v. een platte electrode een elektrisch veld boven de vloeibare lens aangebracht. Dit veld wordt gebruikt voor de manipulatie van het vloeistof-vloeistof (water-olie) grensoppervlak teneinde sferische aberraties te onderdrukken. De meniscus van het de lens is in evenwicht door een balans van de Laplace druk en elektrostatische Maxwell-spanning. Om ons doel te bereiken is kennis nodig over hoe een druppel reageert op een elektrisch veld en welke druppelvorm resulteert in de beste optische prestaties.

Om te beginnen zijn lensystemen gekarakteriseerd door zijaanzichten van het druppelprofiel op te nemen en daarvan de longitudinale sferische aberratie (LSA) te berekenen met behulp van geometrische lichtstraal tracing. Vervolgens worden met Zemax-software via lichtstraal tracing de gemeten meniscusprofielen geanalyseerd en worden numeriek de Zernike sferische aberratie (ZSA) coëfficiënten en andere optische variabelen bepaald.

Daarna is een volledig elektronisch instelbaar optofluïdisch lensysteem ontworpen en gefabriceerd. Dit systeem regelt de achtergronddruk met behulp van electrowetting (EW) en bestuurt het lensprofiel met een andere elektrode. De optische prestaties van het lensysteem zijn experimenteel bepaald door het meten van de ZSA coëfficiënten met behulp van de Shack-Hartmann golffront sensor (SHWS). De gemeten reikwijdte van de EW-afstelbare brandpuntsafstand en sferische aberratie is 10.1mm tot 26.76mm en 0.059 golven tot 0.003 golven respectievelijk.

Hoofdstuk 1 bevat een introductie over optofluïdische lenzen. Het behandelt de voordelen van het gebruik van vloeibare objectieven ten opzichte van gespecialiseerde vaste lenzen. Tevens worden de uitdagingen en limiteringen van vloeibare lenstechnologie uitgelicht. Ook wordt het onderzoek naar en het gebruik van elektrische velden als werkende kracht voor de manipulatie gemotiveerd.


In hoofdstuk 3 worden de verschillende methodes en gebruikte instrumenten voor lenskarakterisatie behandeld. De standaard laboratoriumtechnieken voor golffrontbepaling worden bediscussieerd. Verder worden de wiskundige representaties voor een optisch golffront behandeld. Hierbij gaat het vooral over de decompositie van het golffront in een orthogonale set van Zernike polynomen. Elke polynoom beschrijft een bepaalde vorm van
aberratie. Andere belangrijke optische eigenschappen, zoals de modulatie transfer functie (MFT), Strehl’s ratio, piek-tot-vallei (P-V) en kwadratisch gemiddelde golffront foutwaarde (RMS) die de optische prestaties beschrijven worden in detail behandeld. Ook wordt het optische simulatie platform Zemax, in de context van het modelleren van optofluidische systemen bediscussieerd.

In hoofdstuk 4 wordt de bouw van een optofluidische lens beschreven en de karakterisatie daarvan met lichtstraal tracing in Matlab, gebruikmakende van geometrische optica. Er wordt aangetoond dat door middel van een elektrisch veld de LSA kan worden gereduceerd en zelfs volledig kan verdwijnen als de lens een hyperbolisch profiel aannemen. Dit gebeurt wanneer de excentriciteit van het lensprofiel gelijk is aan de berekeningsindexratio van de lensvloeistof en omringende vloeistof. Experimenteel laten we zien dat het vloeistof-vloeistof grensoppervlak van een druppel, die vastgepind is in een kleine opening, met behulp van elektrostatische krachten kan worden aangepast. Dit wordt ook aangetoond door het scherp kunnen afbeelden van een vierkant raster met behulp van deze, d.m.v. elektrostatische krachten aspherisch gemaakte, vloeibare lens.

In hoofdstuk 5 modelleren en controleren we de optische prestaties van vloeibare lenzen met Zemax. De lenzen worden gekarakteriseerd op basis van de golffront aberraties met de ZSA coëfficiënten en andere standaard optische waarden. De computersimulaties ondersteunen de experimentele resultaten uit hoofdstuk 4. Verder bevestigt een numerieke analyse dat ons lenssysteem superieure optische prestaties en verbeterde beeldkwaliteit heeft vergeleken met standaard sferische lenzen.

Hoofdstuk 6 beschrijft het protocol voor het bouwen van de optische meetopstelling. Deze opstelling is gebouwd voor de golffrontkarakterisatie van lenzen met behulp van de Shack-Hartmann golffront sensor (SHWS). Hiermee zijn experimentele de ZSA coëfficiënten bepaald van lenzen in focus. De betrouwbaarheid is gecontroleerd door de ZSA coëfficiënten te bepalen van twee testlenzen en die te vergelijken met de simulaties van Zemax.

Om onze beweringen verder te valideren, is een robuuster, draagbaar en compact fluidisch lenssysteem ontwikkeld. Hoofdstuk 7 beschrijft de fabricatie en de werking van dit optofluidische lenssysteem. In tegenstelling tot het handgemaakte systeem uit hoofdstuk 4, wordt bij deze verbeterde versie van het vloeibare lenssysteem de Laplace druk geregeld door electrowetting in plaats van het aanbrengen van een hydrostatische druk. We tonen verder de reversibiliteit van het systeem aan door de voltage omhoog en omlaag af te stellen. De ZSA coëfficiënten tonen een vergelijkbare reversibiliteit aan. We laten experimenteel de volledige onderdrukking van sferische aberratie zien door een voltage te plaatsen tussen de diafragma-plaat en top elektrode. Dit is verder aangetoond door het afbeelden van afbeeldingen met verschillende resolutieschaal met deze asferische lens.
List of publications

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Kartikeya Mishra was born on 29th August, 1983 in Raebareli, India. He graduated from Harcourt Butler Technological Institute, Kanpur in 2007. After that, he worked with industry for around two years. In 2009, he enrolled into Masters program in Chemical Engineering at Indian Institute of Technology (IIT), Mumbai. After graduating from IIT Mumbai, he enrolled into doctoral program at University of Twente, The Netherlands under the supervision of Prof. Dr. Frieder Mugele in Physics of complex fluids (PCF) research group. This dissertation is the compilation of the scientific research carried out at PCF.