Adaptive micro-lenses based on electro-wetting

Florian Krogmann, Wolfgang Mönch, Hans Zappe

IMTEK - Laboratory for Micro-optics, University of Freiburg, Germany

mailto:krogmann@imtek.de

The phenomenon of electro-wetting allows manipulating the contact angle of a liquid by applying an electric field between the liquid and an electrode covered by an insulating layer. Using this effect, we present an easy to fabricate micro-lens system, which allows tuning the focal length between 2.3 mm and infinity using 0 to 45 Volts.

1 Introduction

Almost all optical systems can benefit from adaptive optical components. Applications such as cameras, fibre couplers, endoscopes and confocal microscopes can improve their optical field of application by their use.

A promising approach to fabricate micro-lenses is by the use of liquid droplets. Placed on a planar substrate, a liquid forms a spherical cap, which is – from the optical point of view – a plano-convex lens. In this field, many fabrication techniques have been developed. A well-established technology is the melting of photoresist bumps [1]. Another method involves structuring a substrate in hydrophilic and hydrophobic areas on which an UV-curable polymer is placed by dip-coating [2]. All these techniques have the disadvantage that they can not be tuned.

To overcome this limit, the effect of electro-wetting can be used. By using a conductive substrate covered by an insulating layer, it is possible to manipulate the contact angle by applying an electric field between a liquid droplet and the substrate. Therefore, an adaptive optical system can be built in which optical parameters depend on the system's geometry, e.g. initial contact angle, lens volume and refractive index of the lens.

2 Principle

The shape of a droplet is given by thermodynamic equilibrium of the surface energies between substrate and liquid (γ_{SL}), liquid and vapour (γ) and substrate and vapour (γ_{SG}) and is described by the Young-equation [3]

$$\gamma\cos(\Theta) = \gamma_{SG} - \gamma_{SL} \tag{1}$$

with θ the contact angle.

By applying an electric-field between the droplet and the substrate, an additional energy is introduced which is given by the capacitor formed between the liquid and the substrate. This can be described by the Lippmann equation [3]

$$\gamma\cos(\Theta) = \gamma_{SG} - \gamma_{SL} + \frac{1}{2}\frac{\varepsilon}{d}V^2 \tag{2}$$

with ε the dielectric constant of the dielectric layer, d the thickness of the dielectric layer and V the applied voltage. Therefore, application of an electric field to the droplet allows a controlled change in its shape and thus the focal length of a liquid lens.

3 Structure

Due to the liquid nature of the lens, it is necessary to compensate mechanical forces such as vibrations or shock. It is also necessary to eliminate evaporation of the liquid as well as a movement of the lens out of the optical axis. These can be done by including a centering structure into the lens system and filling it with a second, density matched, liquid.

To obtain low driving voltages, it is necessary to use very thin dielectric layers (cf. the 1/d dependence in equation (2)). For that reason, standard MEMS thin-film technology is useful for creating the dielectric layer. It provides very smooth and defect-free surfaces, which reduce hysteresis and increase dielectric breakdown voltages.

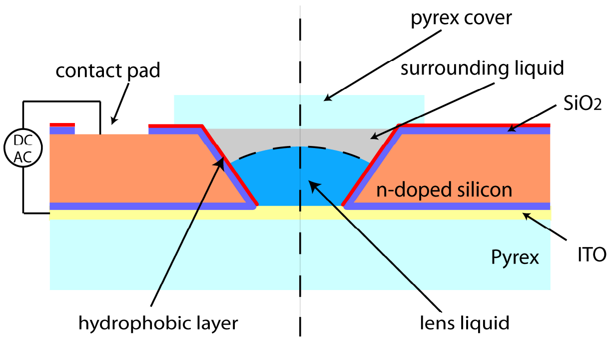

Figure 1: Schematic view of the system discussed in this work.

4 Fabrication

The system is fabricated using standard MEMS technology. This provides highest reproducibility and highest accuracy.

The process starts with an n-doped silicon substrate (1-5 Ωm, (100)-orientation, 525 µm thickness), which is coated with a SiO_2 and SiN KOH-etch mask (110 nm, 400nm). These layers are structured lithographically to obtain quadratic openings. By etching through the wafer using KOH (30%, 80°C), V-groove-based holes with 54.7° sidewalls are formed which act as centering structures for the lenses. Furthermore, the use of KOH-etching techniques provides very smooth surfaces.

After removing the etch mask, the substrate is completely covered with thermally grown silicon dioxide (300 nm thickness). This layer provides very low defects and very high dielectric strength. For contacting the substrate, a bonding area is opened by a RIE process during which the substrate is covered by a shadow mask.

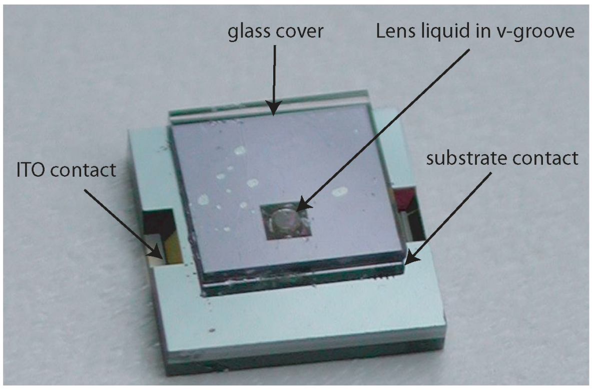

Figure 2: View of the fully fabricated system including lens and surrounding liquid. The bonding of the top Pyrex cover is done by UV-curable adhesive.

To obtain a high initial contact angle - and therefore a low initial focal length – the substrate is covered with a hydrophobic layer.

Afterwards, the system is closed at the bottom with an ITO-structured Pyrex wafer. This is done by a anodic boning process performed in a Suess Bond SB6 Vac bonder. Subsequently, the lens and the surrounding liquid is filled in and then closed by a Pyrex cover, also covered with a hydrophobic layer.

The system can bee seen in figure 2. The aperture – which is the size of the V-groove at the bottom of the substrate – was varied between 300 µm and 1 mm. The dimensions of the whole system are 8 mm x 8 mm x 1.6 mm.

5 Results

All measurements were done by contacting the ITO layer and the substrate and using 1 kHz AC-voltage, which eliminated hysteresis.

The lens liquid is water-based, modified by inorganic salts, which yields a refractive index of 1.51. The surrounding liquid consists of perfluorinated carbons with a refractive index of 1.29. The liquids have identical densities of 2.1 g/cm³.

Using an aperture of 300 µm and 100 nl lens liquid, the lens was able to change back focal length between 2.3 mm and infinity using 0 to 45 Volts. Focal length vs. voltage is shown in figure 3. The initial contact angle of 100° yields an initial back focal length of 2.3 mm. Within measurement tolerances, there was no observation of hysteresis.

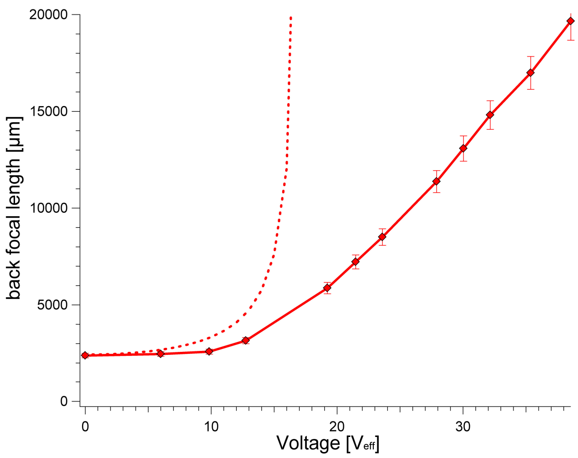

Figure 3: Focal length of a system with an aperture of 300 µm and 100 nl lens liquid.

6 Summary

In this work, an electrically tunable liquid lens was demonstrated. The back focal length was tunable between 2.3 mm and infinity using 0 to 45 Volts. Low driving voltages of 45 Volts for an infinite back focal length and high reproducibility were achieved by using standard MEMS technology.

The use of an equal-density fluid system suppresses the influence of gravity and mechanical shock, such that the system can be implemented in applications which are exposed to vibrations and movements.

7 Acknowledgment

We would like to thank the Landesstiftung Baden-Württemberg and Photonics B.W. for supporting this project.

References

[1] D. Daly: *Microlens Arrays*. Taylor & Francis, 2000, ISBN 0748408932

[2] W. Moench, H. Zappe: *Fabrication and testing of micro-lens arrays by all-liquid techniques*. Journal of Optics A: Pure and applied optics,6:330 – 337, (2004)

[3] B. Shapiro, H. Moon, R. L. Garell, C.-J. Kim: *Equilibrium behaviour of sessile drops under surface tension, applied external fields, and material variations.* Journal of Applied Optics,93: 5794 – 5811, (2003)