Novel components for tunable micro-optics*

HANS Zappe**

Laboratory for Micro-optics, Department of Microsystems Engineering – IMTEK University of Freiburg Georges-Kohler-Allee 102 79110 Freiburg, Germany

(Received 2 September 2007)

We will present some technologies and devices employed for the fabrication of tunable micro-optics. Tunable liquid lenses and lens arrays as well as polymer membrane-based microlenses and scanning mirrors are of both academic and industrial interest in this area.

CLC numbers: TN256 **Document code:** A **Article ID:** 1673-1905(2008)02-0086-3

DOI 10.1007/s11801-008-7113-8

Optical tunability will open new vistas for optical MEMS. A controlled change in the optical properties of lenses, mirrors or filters to allow a tuning of focal length, position, lens curvature or transmission wavelength will provide a new palette of functionality for optical microsystems and enable a wide spectrum of new applications.[1] we discuss here two technologies which have proven to be technically relevant in this area. These include liquid lenses and lens arrays, polymer membrane-based micro-lenses and mirrors. We will outline the device and system performance of these devices, with a view to evaluate the potential for application of these tunable micro-optical components in optical microsystems.

The radius of liquid droplets on a planar substrate may be changed by the application of an electric field between the droplets and the surface, a phenomenon known as electrowetting. Since the droplets have a shape very closely approximating an ideal sphere, they may be used as plano-convex lenses and are the basis for liquid micro-optics.[2] Using transparent liquids with an appropriate refractive index thus allows the fabrication of electrically tunable liquid lenses. By appropriate configuration of the substrate and control electronics, two-dimensional arrays of reconfigurable, tunable micro-lenses may be conceived.[3]

A single tunable liquid lens may be fabricated in a positioning structure which defines the horizontal position of the lens and allows electrical contacting for tuning the focal length. As seen in Fig.1, a cavity etched through a silicon substrate may be used for this purpose. Typical aperture sizes, defined by the size of the bottom opening of the etched structure, vary between 300 μm and 800 μm and the total thickness of the structure is 1.525 mm. The smooth surfaces of the KOH-etched silicon allow precise tuning of the lens, since sticking to surface irregularities is minimized.

The focal length of the lenses incorporated into the cavity may be changed electrically, and the results of focal length measurements are shown in Fig.1(b). With an initial contact

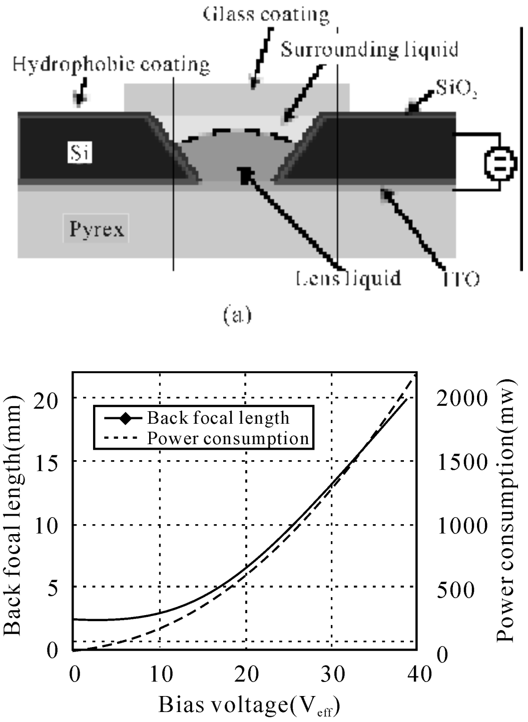


Fig.1 (a) Liquid micro-lens system consisting of a lens cavity fabricated in a silicon wafer using MEMS technology and filled with a high refractive index lens liquid and a low refractive index surrounding liquid; (b) variation of back focal length and power consumption as a function of voltage for a 1 kHz ac driving voltage.

* Antrag GZ398, Chinesisch-Deutsches Zentrum für Wissenschaftsförderung,2006.

** E-mail: zappe@imtek.uni-freiburg.de

angle of 96°, yielding a back focal length of 2.3 mm (V = 0), the application of an ac voltage of 45 V results in a back focal length of infinity, i.e. a planar surface. These measurements were performed on a lens with an aperture of 300 μm. The rms surface roughness was seen to be less than 3 nm, such that this tunable lens system was seen to be diffraction limited when operated at visible wavelengths. By measuring the voltage and the current, as well as the phase angle, the power consumption could be calculated and shown a maximum of about 2 mW when the bias led to an infinite focal length.

Electro wetting also has been proven to be a useful approach for the manipulation of the position of liquid lenses. A repositionable micro lens system in which the lenses can be precisely positioned laterally, and also the focal length tuned dynamically independent of the lens position on the chip, has been demonstrated.

If a droplet positioning system requires a high positioning accuracy, a high spatial density of electrodes is also generally required. Since a high electrode number implies complex and extensive control electronics, a design has been developed which allows precise control of the position of the liquid lens with a relatively coarse electrode pitch.[4] Using an etched surface grid, the application of a succession of voltage pulses allows accurate positioning at various locations on a single electrode. After the droplet is moved to the desired position, its focal length can then be tuned by applying a uniformly varying potential to all surrounding electrodes under the droplet.

Using this approach, 600 μm diameter liquid lenses could be arbitrarily positioned with an accuracy of 70 μm on a patterned, transparent substrate, as seen in Fig.2. Once brought into position, the lenses could subsequently be tuned in focal length in the range of 3.7 to 5.5 mm. This concept is presently being expanded to allow independent positioning and tuning of multiple lens arrays on a single substrate.

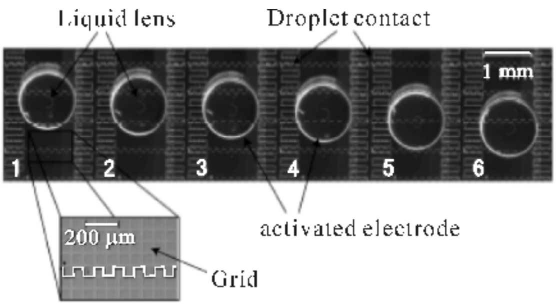
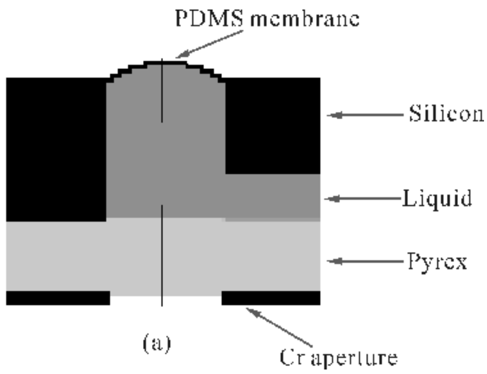


Fig.2 A succesion of photographs showing the repositioning of a liquid lens along an electrode array from top to bottom;the grid period defines the positioning accuracy.

A tunable liquid lens may be also conceived using a completely different approach, namely that of a silicon-based micro-fluidic cavity and a distensible PDMS-based membrane defining the lens surface.[5] As shown schematically in Fig.3, changing the pressure of the liquid in the cavity will cause the membrane to expand, defining a spherical lens surface. The membrane itself, with a thickness less than 50 μm, has no optical function and merely defines the shape of the liquid volume, and the liquid itself is the lens medium.

With apertures ranging from 300 to 600 μm, these micro-lenses are tuned by pressure. By increasing the pressure of the liquid in the cavity, the membrane expands, thereby decreasing the radius of curvature of the spherical surface and thus increasing its optical power. Using liquids with refractive indices ranging from 1.35 to 1.6, application of pressures up to 54 kPa results in focal lengths from 1 to 18 mm at λ= 550 nm, and the minimum radius of curvature achievable is about 0.2 mm. The elasticity of the membrane is such that it may be expanded to a point corresponding to a half-sphere on the substrate.



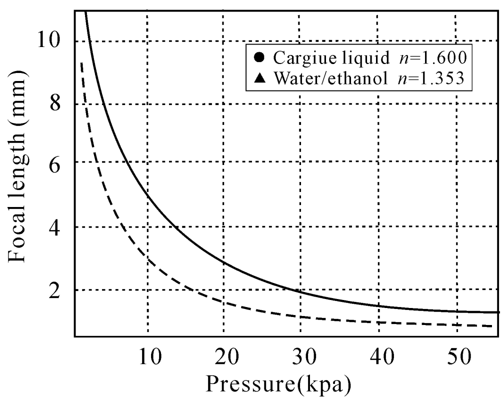


Fig.3 (a) Cross-sectional diagram of a membrane-based micro-fluidic micro-lens;the cavity is liquid-filled and variations in pressure tune the curvature and hence the focal length of the lens ;(b) focal length of 400 μm membrane lenses as a function of applied pressure for two different liquid media:1:1 water/ ethanol and proprietary optical liquid.

Due to the fact that the membrane is fixed to the surface of a planar substrate, the distended membrane is not ideally spherical over its entire diameter, but the optical aberrations may be reduced by employing an aperture smaller than the membrane diameter.

The variation of focal length of the tunable micro-lens depends not only on the radius of the distended PDMS membrane but also on the refractive index of the liquids employed as the lens medium. The effect of refractive index is seen clearly in Fig.3. The choice of liquid thus allows the user to shift the tunable pressure range to correspond to the desired range of focal length values.

These membrane-based tunable lenses may be tuned over a wide range of positive and negative curvatures and thus positive and negative focal lengths. Membrane-based optics may be also expanded to cover a range of further tunable micro-optical elements, in particular pneumatically-actuated scan as well as tip-tilt micro-mirrors.[6, 7]

Tunable micro-lenses based on the concepts described above are of considerable value in compact optical systems with enhanced functionality and are being developed, for example, for use in endoscopic optical coherence tomography systems.[8] Numerous other technologies have become relevant for tunable microoptics in general, particularly silicon-based opto-thermal filters[9] and polymer structures with controlled swelling.[10, 11]

The author is indebted to Florian Krogmann, Riyaz Shaik, Wolfgang Monch and Armin Werber of the Laboratory for Micro-optics, whose work is presented above.

References

[1] C. Friese, A.Werber, F. Krogmann,W.M¨onch, and H. Zappe. IEEJ Transactions on Electrical and Electronic Engineering, **2** (2007), 232.

[2] F. Krogmann, W. M¨onch, and H. Zappe. Journal of Optics A: Pure and Applied Optics, **8** (2006) 330, July .

[3] F. Krogmann, R.P. Shaik, W. M¨onch, and H. Zappe. In Technical Digest of the IEEE International Conference on Micro Electro Mechanical Systems (MEMS 07), (2007), 707.

[4] R.P. Shaik, L. Lasinger, F. Krogmann, W. M¨onch, and H. Zappe. In Technical Digest of the 2007 IEEE/LEOS International Conference on Optical MEMS and Nanophotonics, (2007),139.

[5] A. Werber and H. Zappe. Applied Optics, **44** (2005), 3238.

[6] A.Werber and H. Zappe. Journal of Micromechanics and Microengineering, **16** (2006):2524 .

[7] A. Werber and H. Zappe. Journal of Optics A: Pure and Applied Optics, **8** (2006), 313.

[8] K. Aljasem, A. Werber, S. Reichelt, D. Mader, and H. Zappe. In Proceedings of Transducers 07, **2** (2007), 2557.

[9] D.Hohlfeld and H. Zappe.IEEE Journal of Microelectromechanical Systems, **16** (2007), 500.

[10] W. Mönch, J. Dehnert, E. Jaufmann, and H. Zappe. Applied Physics Letters, **89** (2006), 164104.

[11] W. Mönch, J. Dehnert, O. Prucker, J. Rühe, and H. Zappe. Applied Optics, **45** (2006), 4284.