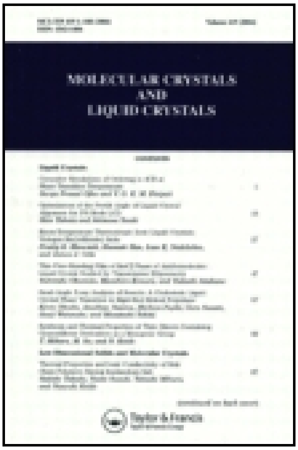

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HIGH QUALITY ADAPTIVE LIQUID CRYSTAL MICROLENSES

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High Quality Adaptive Liquid Crystal Microlenses

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An adaptive microlens was built with planar aligned liquid crystal and circular electrode structure on one side of a sandwiched liquid crystal cell. The fringing effects at the edges of the electrodes produce a spatial distribution of the electric field. Applying a voltage deforms the liquid crystal director field. This produces an axial asymmetric profile of the extraordinary refractive index. The liquid crystal cell becomes a convex (converging) lens. A dual frequency liquid crystal mixture was used to study the influence of material parameters on the lens quality. We found that the quality of the lens is best if the lens diameter is approximately one and a half the cell thickness. For such microlenses diffraction limited lens properties with Strehl intensities of 0.9 are measured. The lenses show off-axis properties. In the diffraction limited regime, a focal length change of approximately 18% is obtained for different electric control parameters.

Keywords: microlens; liquid crystal; diffraction limited; variable focal length

INTRODUCTION

Liquid crystal microlenses have been investigated for a long time. During the years several configurations were studied. There are microlenses immersed in liquid crystal [1-3], fringing field microlenses [2, 4-9], binary Fresnel zone arrays [10] and modal control lenses [11-13]. All of them have a limited range for varying the focal length and the optical quality changes with the focal length. In combination with our conventional microlens technology [14] it seems preferable for us to use fringing field microlenses with planar aligned liquid crystal. These lenses can have very good imaging properties in linear polarised light [15]. The fringing of the electric field at the electrode edges is responsible for the reorientation of the liquid crystal nematic director. Therefore a change in the response of the liquid crystal to the electric field seems promising to improve the optical properties over a range of focal lengths. In this paper we want to discuss liquid crystal microlenses using a double frequency nematic mixture DF30 (from Chisso with $\varepsilon_p(1\text{kHz}) = 7.5$, $\varepsilon_s(1\text{kHz}) = 5$, $\Delta\varepsilon(1\text{kHz}) = 2$, transition frequency about 30 kHz) to change the fringing electric field properties.

SIMULATIONS

To explain the influence of the liquid crystal parameters on the adaptive lens, the director field has been simulated (elastic constants $K_{11} = 15$ pN, $K_{22} = 10$ pN, $K_{33} = 20$ pN). We used a commercial program (LCD Master from Shintech [16]) to get the three-dimensional birefringence profiles and we calculated the optical properties in a collinear approximation with the Jones matrix method [17]. As an example, a calculated wavefront is shown in Figure 1. The nematic director profile is simulated for a planar liquid crystal slab sandwiched between electrodes. The diameter of the lens is determined by the hole in one of the electrodes and is 80 μm The cell thickness is 50 μm. The extraordinary and ordinary refractive indices used for the calculation are $n_e = 1.727$ and $n_o = 1.516$ respectively. After fitting and subtracting a spherical wave from the calculated

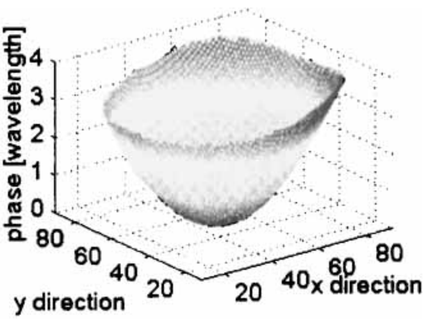

FIGURE 1 Calculated wavefront of a gradient index liquid crystal microlens. The voltage applied is 7 V and the dielectric anisotropy was $\Delta\varepsilon = 2$. A slight asymmetry is visible.

wavefront, aberrations as the deviations from the spherical wave are found. We calculated the Strehl intensity [18] and the focal length to characterise the adaptive lenses. The most interesting liquid crystal parameters are the elastic constants [19], the pretilt angle and the dielectric anisotropy. The elastic constants give the anisotropic distortions and detailed discussions of their influence are difficult. The pretilt angle at the surface gives a preferred direction of reorientation and results in an asymmetrical liquid crystal director distribution [15]. This causes a tilt of the liquid crystal lens. The dielectric anisotropy determines the fringing electric field in the liquid crystal cell. In the configuration chosen, the pretilt angle and the influence of the different electric constants of the adaptive lens will not be discussed further. The change of the dielectric anisotropy with frequency is the most interesting effect, because it allows a continuous change of the nematic director configuration inside the cell. The nematic director field has been simulated with the assumption that a certain dielectric torque [20] on the director is necessary to obtain the desired phase shift, hence the product $\Gamma_{diel} = \Delta\varepsilon\varepsilon_0 E^2$ should be about the same for different values of the dielectric anisotropy $\Delta\varepsilon$. Table 1 summarises the simulation results for an 80 μm diameter lens.

Dielectric anisotropy	Voltage [V]	$\Delta\varepsilon V^2$ [V^2/m^2]	Focal length [μm]	Strehl intensity
2	7	98	567	0.598
1	10	100	595	0.612
0.5	15	112.5	652	0.599

TABLE 1 Simulation results for varying dielectric anisotropy. The dielectric torque on the nematic director and the lens quality is about the same, but the focal length changes. The cell thickness is 50 μm.

In our simulated examples the focal lengths are changing about 15% and the Strehl intensity does not change much. The optical quality is very sensitive to the applied voltage. In experiments it was found, that the driving voltage could be optimised for the best optical quality over a range of about 1 V without change of the focal length [15, 21, 22]. Although we did not use the optimal simulation parameters for the driving voltage there is a shift in the focal length and the optical quality does not change. That will also be found in the experiment. The change of the fringing field and the corresponding director field deformation should allow the construction of a microlens with variable focal length with good optical quality.

EXPERIMENTAL

We fabricated microlens arrays with planar aligned liquid crystal and standard technology. After etching holes in the chromium electrode on the glass substrate the alignment polymer (PI 2454 from Nissan) was spin-coated and rubbed to give strong anchoring with a pretilt angle of 3°. The counter-electrode was a transparent indium tin oxide (ITO) electrode on glass and was treated with the same alignment procedure. With the two substrates, an anti-parallel planar aligned cell with a thickness of 50 μm was assembled as shown in Figure 2. Different diameters of holes were chosen to search the best geometrical

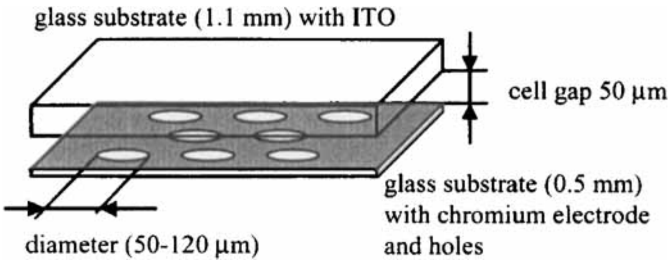

FIGURE 2 Liquid crystal cell with a hexagonal arrangement of the holes in the chromium electrode. The liquid crystal orientation is planar due to anti-parallel rubbing of polyimide substrates.

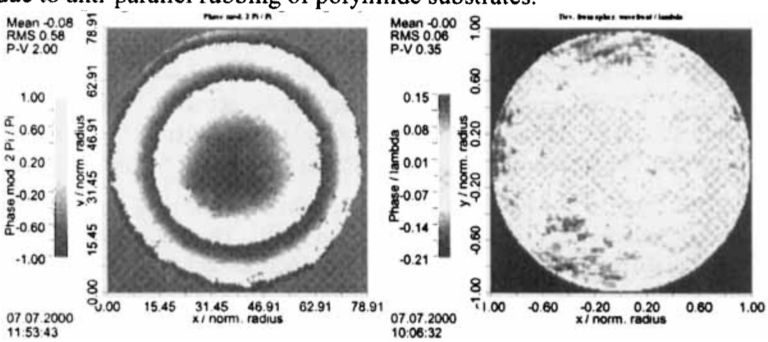

FIGURE 3 Measurements at a microlens with 80 μm diameter driven with 6.5 V at 10 kHz. Left: Phase profile. The maximum phase shift is aproximatly two wavelength. Right: Abberations. The effective value of the abberations is 0.06 wavelength.

configuration. The quality of the microlenses was measured with a Mach-Zehnder interferometer [23] and the focal length was determined by microscope inspection. As an example, the phase profile under plane wave illumination and the aberrations are shown in Figure 3. The measurements are done in linear polarised light. A maximal phase shift of two times the wavelength was found in the left picture of Figure 3 and a slight asymmetry of the interference fringes is visible. The effective values of the aberrations on the right side in Figure 3 are very small with an effective value of about 0.06 wavelength. The lens is nearly diffraction limited. The measurements do not allow the determination of tilt of the lens. Therefore the lens tilt is measured evaluating the phase profile in plan wave illumination. For the example in Figure 3, a lens tilt of 0.1° was found. The lens tilt changes with the voltage and can be as high as 3° [15].

This results show, that a nearly diffraction limited lens can be realised for a certain geometry and liquid crystal. In Figure 4 the Strehl intensity and the focal length are shown as a function of the lens diameter. The driving voltage differs for different diameters. For larger diameters of the electrode hole the focal length increases and the Strehl intensity decreases. However, it was not possible to get diffraction-limited performance for diameters larger than 100 μm.

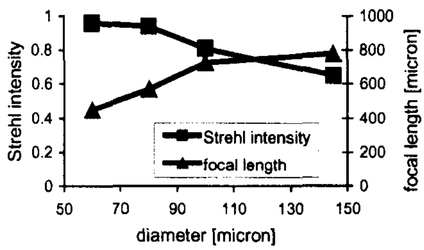

FIGURE 4 Measured Strehl intensity and focal length for different diameters of the liquid crystal microlens. (1 kHz)

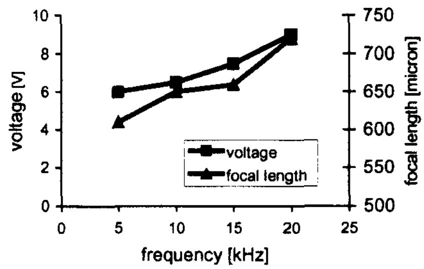

FIGURE 5 Frequency dependence of the focal length and the driving voltage (rms) of the 80 μm diameter diffraction limited adaptive lens.

The double frequency mixture DF 03 allows to change the dielectric anisotropy form $\Delta\varepsilon = 2$ at 1 kHz to negative values for frequencies above 30 kHz. That means by varying the frequency we can change the distribution of the non-uniform electric field. The frequency dependence has been studied for the most promising geometry of 80 μm diameter of the electrode hole and the results are shown in Figure 5. We have been looking for the best Strehl intensity as a function of frequency and voltage (left scale) and than measured the focal length (right scale). The Strehl intensity in the measurements sown in Figure 5 was always greater than 0.85. For diffraction limited operation the focal length changes from 610 μm to 720 μm, thus by 18%. Thus we have a lens that is diffraction limited for linear polarised light and can change the focal length. For higher frequencies the operation of the lens becomes unstable because of the vanishing dielectric anisotropy.

DISCUSSION

The adaptive liquid crystal microlens with planar alignment is a gradient index lens. The fringing electric field at the circular electrode reorients the liquid crystal molecule through the dielectric anisotropy of the liquid crystal. For a large dielectric anisotropy the fringing electric field can be considerably different for the direction parallel and perpendicular to the alignment. For large dielectric constants, the electric field is less extended into the electrode hole than for smaller ones. Therefore, if one changes the dielectric constant by changing the frequency, the extension of the fringing electrical field can be changed.

The dielectric torque gives the reorientation of the nematic director in an electric field and is given as $\Gamma_{diel} = \Delta\varepsilon\varepsilon_0 E^2$ [20]. The smaller the dielectric anisotropy and the electric field, the weaker is the torque on the molecule. In the continuum model [24], the electric torque is balanced by the elastic deformation properties of the liquid crystal. For smaller dielectric constants, the fringing electric field extends larger into the electrode hole and the dielectric torque on the liquid crystal molecule is smaller. These can result in a different distortion of the liquid crystal director and refractive index distribution. From the measurements we know, that the voltage level has to be increased with increasing frequency to get a liquid crystal lens. The simulations and the measurements show that in our case the reorientation for a smaller dielectric anisotropy and constant dielectric torque becomes smaller.

The main contribution to the optical phase shift of the gradient index lens is given by the nematic director tilt angle that determines the effective birefringence. For weaker distortion of the director field the tilt angle decreases and the effective birefringence becomes smaller. The focal length of the lens increases with decreasing dielectric anisotropy, hence with increasing frequency. That is verified in the measurements shown in Figure 5.

The measured Strehl intensities in Figure 5 are greater than the simulated ones listed in Table 1 because the simulations do not take the hexagonal array of the microlenses into account. In addition, the voltage in the simulation is not the optimal voltage for the highest Strehl intensity.

CONCLUSION

A non-uniform distribution of the liquid crystal director has been used to form an adaptive liquid crystal lens. The change of the dielectric anisotropy with frequency of a double frequency liquid crystal mixture has been used to control the fringing electric field. A diffraction limited adaptive lens has been demonstrated, which changes the focal length without loss of the high optical quality. The lens has a very small tilt and is sensitive on the polarisation of light.

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