Electrode designs for tunable microlenses

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Introduction

A changeable focal length is essential to many optical systems. Commonly, such systems employ a mechanical solution which can create problems for the designer in terms of excessive power consumption, slow response time, price and the reliability problems of moving parts. An alternative non-mechanical approach is being investigated at UCL using liquid crystal immersed microlenses [1]. In this paper, we investigate electrode structures in order to improve the performance of the lenses.

Microlenses have been fabricated and immersed in nematic liquid crystal to give an electrically controllable focal length. The liquid crystal material is uniaxially birefringent and the effective birefringence can be controlled since the director, the average direction of the molecules, reorientates towards an applied electric field. Thus, for light polarised parallel to the liquid crystal slow axis, the refractive index can be voltage controlled and, consequently, when a lensing interface is formed between a refractive material and the liquid crystal, the overall lens focal length can be voltage controlled (see figure 1). The lensing properties of this design have been reported previously [1] and it was reported that a disclination initially forms in the liquid crystal upon application of an electric field and that some of the light polarisation is modified with respect to the input polarisation. The disclination causes light scattering and both the disclination and the polarisation modification would need to be eliminated for most systems.

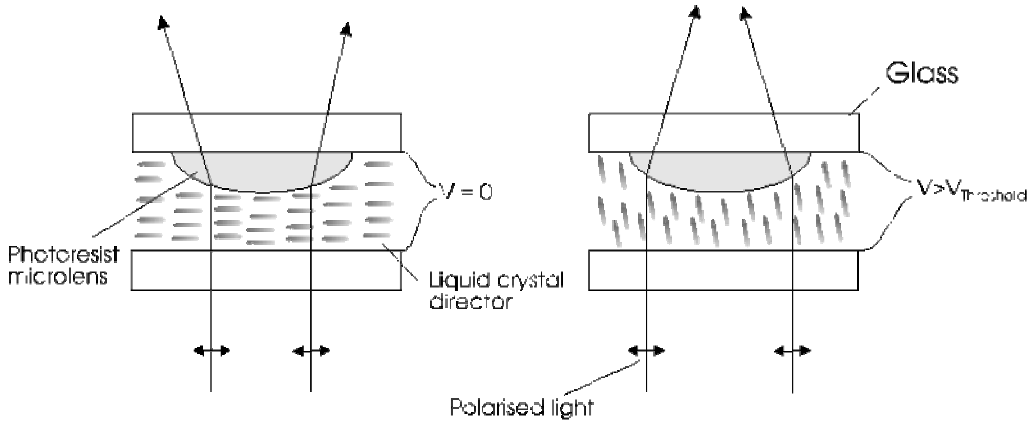


Figure 1: Basic design of liquid crystal immersed microlens

A disclination is analogous to a dislocation in a solid crystal except that in a liquid crystal the structure is more dynamic. The disclination occurs because the liquid crystal reorientates to be parallel to the applied field but with no particular polarity causing a degeneracy. In the most common liquid crystal cell designs (displays), a small orientation offset with zero-field would usually overcome this problem but, in our case, the lens shape causes a larger opposite offset on one side of the lens. The disclination forms a loop which has an initial diameter roughly equal to the diameter of the lens but is offset such that one side of the loop passes through the centre of the lens. The loop shrinks down and disappears in about a minute and does not reappear unless the voltage drops below threshold and then rises above it again.

The change in the polarisation of the light transmitted occurs for voltages above the threshold voltage (and after the disclination has disappeared). Only the light nearer the edge of the lens is affected. As the voltage increases beyond the threshold the effect becomes more pronounced, altering the polarisation of the light closer to the centre of the lens. Thus, there is, in effect, a partial aperture obscuration and then, unless a polariser is incorporated, there is a second partial aperture to be considered (in the other polarisation).

One of the conclusions from our previous measurements of the phase aberrations of the original lens design was that part of the aberration (the dip in the centre) was due to the reduced thickness of the liquid crystal over the centre of the microlens. The result of the thinner liquid crystal layer is that the surface anchoring forces (which cause the liquid crystal to lie in the plane of the cell with no field applied) have a proportionately greater effect. In this paper, a new design with an electrode on top of the microlens is investigated in order to correct the liquid crystal response. Other electrode designs are considered which might reduce the disclination and polarisation problems.

Design

With regard to liquid crystals, a 2 dimensional structure is simpler to study than a 3 dimensional one, thus, for our new designs, we started with cylindrical lenses immersed in liquid crystal. The first new design made was a 'slice' (in the rubbing direction) through the original spherical microlens for comparison with the spherical lens. The next design was suggested by Fabrizio Di Pasquale from his liquid crystal modeling work [2]. He proposed that a strip electrode, twice the lens width, opposite the photoresist microlens would reduce the disclination. The other design, as mentioned previously, was to place the electrode on top of the photoresist microlens to improve the uniformity of liquid crystal switching.

Fabrication

The lenses are photoresist microlenses (diameter 100μ m, focal length in air 100μ m) made by melting and reflow [3] on Indium Tin Oxide (ITO) coated glass which then forms one wall of a liquid crystal cell. The ITO is a transparent electrode necessary for applying an electric field to the liquid crystal. Both walls are spin coated with a polyvinyl alcohol (PVA) alignment layer which is rubbed with a cloth to define the alignment direction. The cells are then backfilled with liquid crystal.

The cylindrical lens cells were made in the same way except using a mask of rectangles 100μ m wide and 4mm long. The rubbing direction was perpendicular to the long axis of the microlens. The strip electrodes were made from a thin film of chromium (8nm) which does not have a high transmittance (20%) but which is easy to deposit by evaporation and pattern for test devices. ITO can also be patterned but the process is more complicated. The electrodes are 200μ m wide strips and centred on the same line as the lenses so that the electrodes extend out 50μ m either side of the lenses. The cells with an electrode on top of the microlenses were also fabricated using a thin film (8nm) of chromium. The two substrates were aligned using optomechanical mounts and a microscope for inspection and then glued together with UV curable glue separated by 27μ m Mylar spacers.

Cylindrical lens measurements and results

The polarisation changing properties of the liquid crystal immersed microlens were studied by inputting a laser beam polarised parallel to the rubbing direction and then imaging the microlens with a microscope objective followed by a polariser (perpendicular or parallel with respect to the original laser polarisation) and finally a CCD camera. This is shown, as part of a more general set-up, in figure 2.

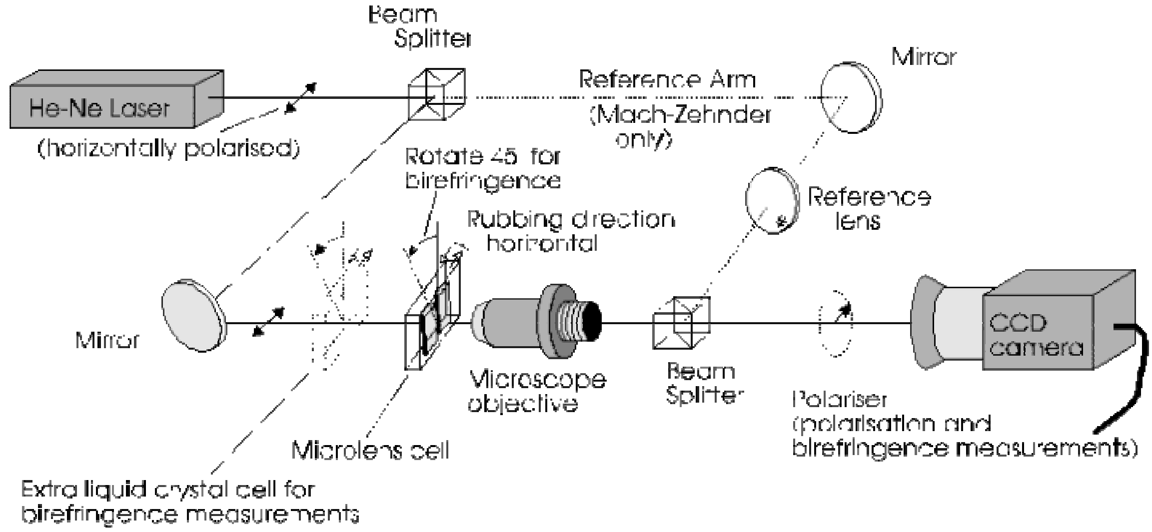


Figure 2: The interferometer setup used as a Mach-Zehnder, for birefringence measurements and

for polarisation measurements

The plots of the transmitted intensity through parallel and crossed polarisers can be seen in figure 3. The new designs show a significant improvement in the polarisation change caused by the liquid crystal structure but with the strip electrode (figure 3(b)) there is a disclination down the centre of the microlens.

(a) (b) (c)

Parallel polarisers:

Crossed polarisers:

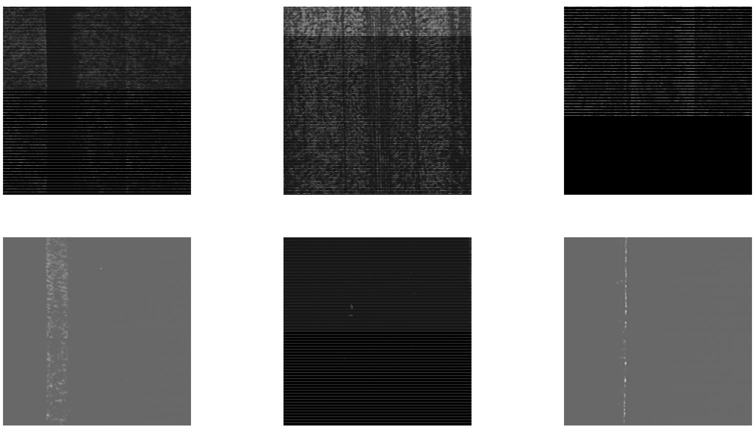
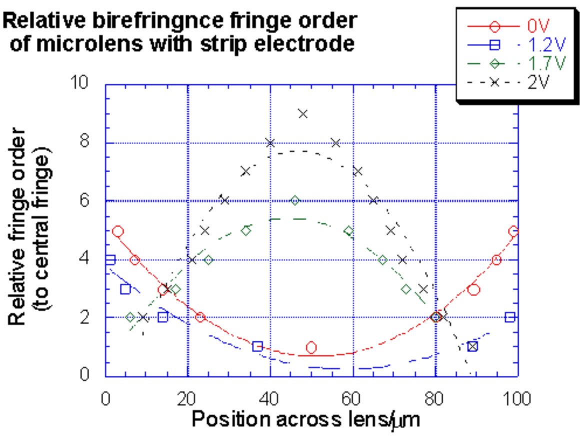


Figure 3: The cylindrical lenses (original (a), strip electrode (b) and electrode-on-top (c)) as seen through crossed and parallel polarisers, input polariser parallel to rubbing direction with 8V applied.

The cylindrical lenses were tested by measuring the birefringence fringes of the liquid crystal. The experiment is again shown in figure 2. The set-up used to measure birefringence fringes consists of a polarised laser beam normally incident on the lens cell with the polarisation arranged at 45 deg. to the rubbing direction. The microlens is imaged by a microscope objective onto a CCD camera. A polariser is placed in between the objective and the camera orientated parallel to the original input polarisation. Thus, dark and light fringes are seen when the half and full waveplate conditions are met by the liquid crystal.

A second liquid crystal cell (with no lenses) was inserted in the laser beam before the first with its rubbing direction parallel to the first to provide an extra controllable birefringence in order to be able to shift the fringes and determine their order. The fringe positions and order was recorded from a monitor screen.

The birefringence plots of the strip electrode design (see figure 4a) show the effect of the disclination forming at 2 volts. This causes the profile to cease being lens-like (which can be seen from the curve fitting of a 2nd order polynomial which becomes inaccurate). In the plots, for the cylindrical lens with the electrode on top of the lens (see figure 4b) the most noticeable effect is the tilt which is greatest at 2V. The cylindrical version of the original microlens design cannot be investigated from its birefringence fringes since the liquid crystal forms a twisted structure (see figure 3(a)) making the fringes impossible to interpret without a detailed knowledge of the structure.



(a)

(b)

Figure 4: Birefringence fringe positions across the microlenses

From the results so far, it can be seen that strip electrode design gives a much better polarisation performance but there is still a disclination. The design with the electrode on top of the lens gives an improved polarisation performance and no disclinations.

Spherical lens measurement and results

From the results of the cylindrical microlenses, it was decided that it would be worthwhile fabricating a spherical microlens with an electrode on top. This was done as with the other lenses but using the spherical mask. The spherical microlens design also did not produce a disclination in the liquid crystal. The polarisation modification was improved with respect to the original design of lens but was not completely eliminated as was the case on the cylindrical lens.

The spherical microlenses were tested in a Mach-Zehnder interferometer (figure 1) and the fringe patterns were analysed by fringe analysis software. The measured aberrations of the spherical lenses were much reduced relative to the original design (figure 5). The measured aberrations are lowest where the focal length is changing fastest (1-2V). It should be remembered that the tilt (shown in the birefringence measurements) is not included in the aberration measurement since the fringe analysis software removes it.

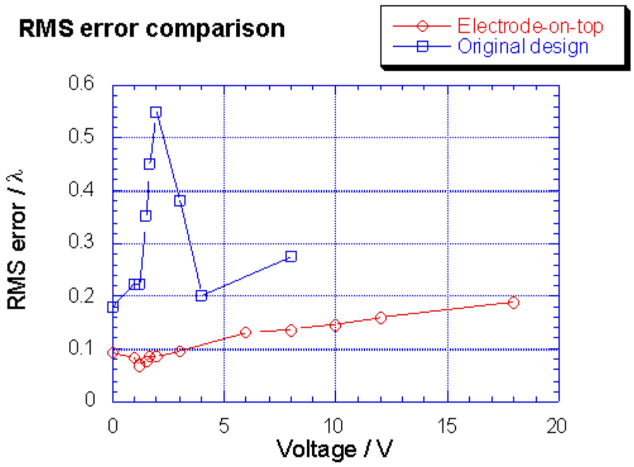


Figure 5: RMS error of original and new design of spherical microlenses

Conclusions

Four new liquid crystal immersed microlens designs have been considered, three cylindrical and one spherical. One was a cylindrical version of a previous design, another was the same but with a strip electrode on the other liquid crystal substrate, the third cylindrical lens had an electrode on top of the photoresist lens and, finally, a spherical lens was fabricated also with an electrode on top.

The lenses have been investigated with regard to their liquid crystal disclination and polarisation modifying properties. It was found that the cylindrical lens version of the previous design, like its spherical counterpart, caused a disclination in the liquid crystal and changed the polarisation of some of the light transmitted. By using a strip electrode on the opposite substrate, the polarisation change was eliminated but the disclination at the centre of the lens was not. However, the design with an electrode on top of the cylindrical microlens eliminated both the polarisation change and the disclination. Due to this success, a spherical microlens was fabricated with an electrode on top of the lens. This design also eliminated the disclination and showed an improved polarisation performance. The structure adds tilt to the transmitted beam but the measured aberrations of this lens were much improved with respect to the original design.

Acknowledgments

The authors would like to thank David Prescott for microlens fabrication, Fabrizio Di Pasquale for modeling work and the UK EPSRC and Royal Society for financial support.

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