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Adaptive modally addressed liquid crystal lenses

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ABSTRACT

An adaptive lens, which has variable focus and is rapidly controllable with simple low-power electronics, has numerous applications in optical telecommunications devices, 3D display systems, miniature cameras and adaptive optics. The University of Durham is developing a range of adaptive liquid crystal lenses, and here we describe work on construction of modal liquid crystal lenses. This type of lens was first described by Naumov [1] and further developed by others [2-4]. In this system, a spatially varying and circularly symmetric voltage profile can be generated across a liquid-crystal cell, generating a lens-like refractive index profile. Such devices are simple in design, and do not require a pixellated structure. The shape and focussing power of the lens can be controlled by the variation of applied electric field and frequency. Results show adaptive lenses operating at optical wavelengths with continuously variable focal lengths from infinity to 70 cm. Switching speeds are of the order of 1 second between focal positions. Manufacturing methods of our adaptive lenses are presented, together with the latest results to the performance of these devices.

Keywords: liquid crystals, adaptive lens, modal addressing, adaptive optics

1. INTRODUCTION

In conventional optical systems, features such as variable focus and zoom can usually only be achieved by use of lenses combined with complex mechanical positioning systems. The performance of such devices is severely limited by the speed at which lenses can be repositioned relative to each other. In addition, the bulky and heavy motorised positioning systems are often impractical, especially in miniature cameras or space-based applications for example. Small, and lightweight variable focus lenses, with rapidly changing and electronically controllable focal lengths, are therefore a subject of detailed investigation and research.

Optical lenses with a single static focus can be fabricated in two different ways. The more familiar type consists of a material of constant refractive index that has been shaped to generate an appropriately varying optical path length across the profile of the device. In the alternative configuration, the device is flat and has a constant optical path length across its profile, but instead induces lensing by use of a spatially varying refractive index.

Variable focussing of a conventional optical lens can be created by mechanically deforming the lens into thinner or fatter lens profiles, a method that is utilised by the human eye. This changes the optical path length across the profile of the lens, whist maintaining a constant refractive index. Another example of a device using this technique is an elastic lens with variable liquid-filled volume [5]. Another approach is to vary the contact angle between a liquid drop and the surface upon which it rests by varying an applied voltage at the interface [6]. A voltage controlled oil-water meniscus lens with variable focus (called "FluidFocus") is in development by Philips [7], and a similar technology is also being developed by Varioptic [8].

Alternatively, variable focussing can be achieved by dynamically changing the refractive index of the medium from which the lens is made. The birefringent properties of liquid crystals and electro-optic crystals can be used to generate this. However, liquid crystals are usually preferred due to their large birefringence and low control voltages. By filling a lens-shaped cavity with liquid crystal, and applying a constant voltage across the cell, it is possible to change the refractive index of the medium for incident plane polarised light, thus producing a variable focus lens [9-11].

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A uniform thickness adaptive lens device would be simpler to manufacture than a lens-shaped device. However, it would require a spatially varying and controllable refractive index profile in order to function appropriately. This could be created with a spatially varying and controllable electric potential across a liquid crystal cell. An appropriate electrode structure would therefore need to be constructed, sandwiching the cell. One solution is to use a pixellated (or zonal) electrode structure [12]. However, this gives only a step-wise approximation to the required field, and also incurs other problems such as fill-factor losses, diffraction of light at pixel boundaries and complicated multiple electrode structure and addressing software. Another example is the acousto-optic lens [13, 14]. Unfortunately, such devices are weak lenses and have highly complex electrode structures and drive electronics.

Very small aperture liquid crystal microlenses have been demonstrated, which utilise the fringing electric fields surrounding very small apertures made in the control electrodes of simple liquid crystal cells [15-17]. This solution removes the need for pixellated zonal addressing, making the device far simpler to manufacture and avoiding the step-wise features associated with pixellated devices. However, the lens profile can only be controlled by varying the amplitude of the control voltage. Aberrations are problematic, and lens apertures are also restricted to micro-scales.

An alternative method of generating a lens-like voltage profile across a liquid crystal lens is by modal addressing [1-4]. This unique design also eliminates the need for pixellated electrodes or other complex structures, and allows fine tuning of the lens characteristics through simple variation of both frequency and amplitude of the driving voltage. Large focal ranges are therefore achievable, together with a wide possible range of lens apertures. This paper looks at our manufacturing methods used to fabricate modal lenses, and presents preliminary results to their operating characteristics.

2. THEORY

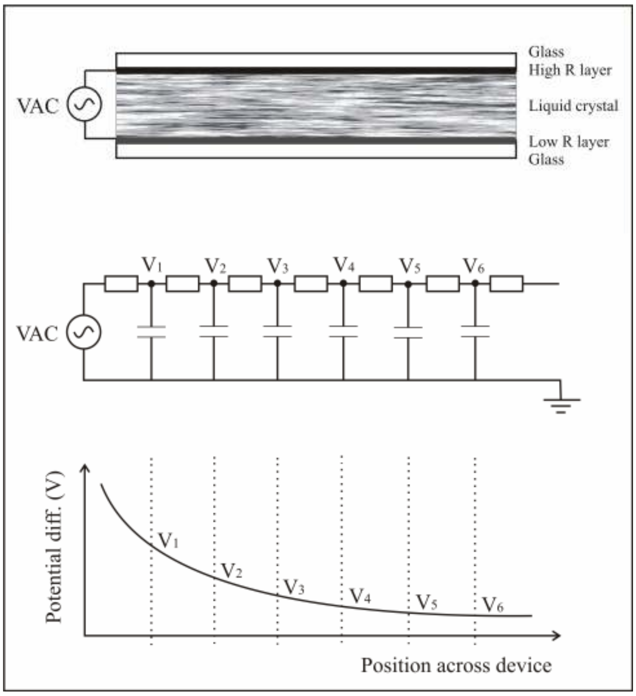

Fig. 1. Simple liquid crystal cell with high resistance electrode, AC driven from one end only, and corresponding equivalent circuit and voltage profile.

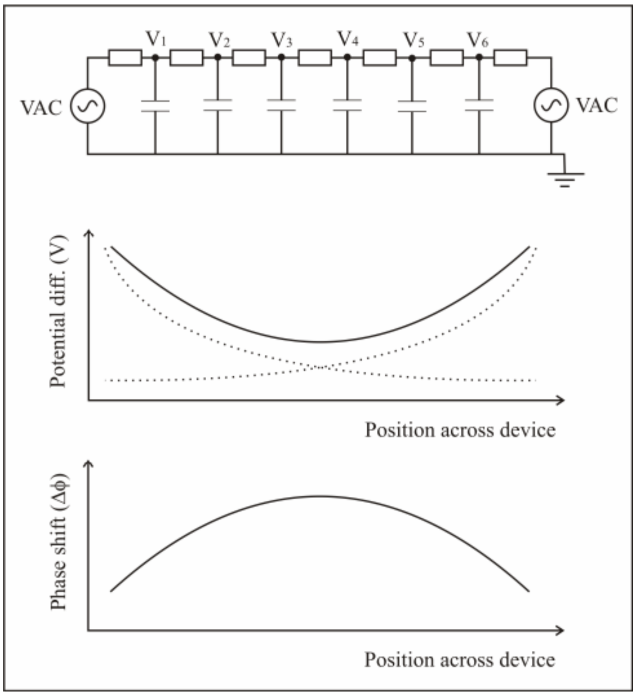

Fig. 2. Equivalent circuit for simple liquid crystal cell with high resistance electrode, AC driven at both ends, and corresponding voltage and phase profile.

First we review the principle of modal addressing. Modal addressing uses a simple electrode structure to generate a quasi-parabolic and circularly symmetric voltage profile across the profile of a liquid crystal cell. This in turn causes the phase profile of the transmitted light to resemble a spherical lens shape. The mechanism by which such a voltage profile is generated is described below.

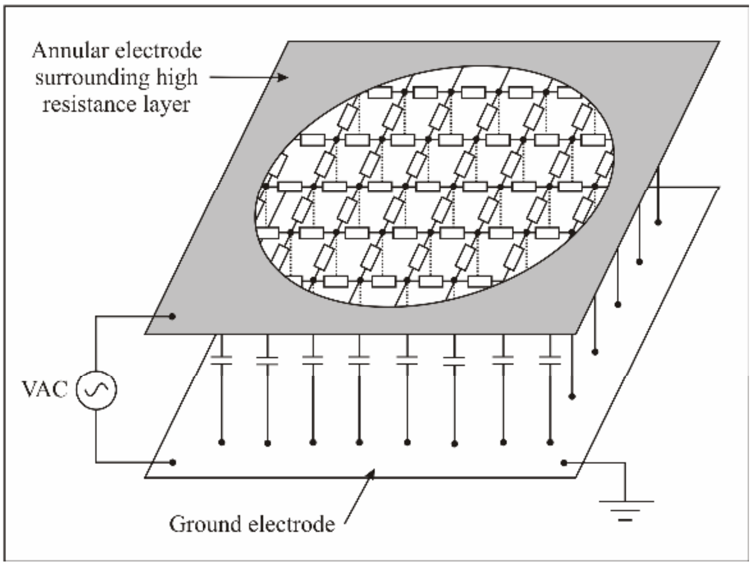

Fig. 3. Equivalent circuit for a modal liquid crystal lens.

Consider a simple liquid crystal cell, with two electrodes sandwiching the liquid crystal within the centre cell. It is driven with a sinusoidal potential, and the orientation of liquid crystal molecules responds to the corresponding root-mean-square voltage (V_{rms}) that is applied. The liquid crystal sandwiched between the two electrodes can be considered to be similar to a small capacitor (combined with a very small parasitic parallel conductance, due to dielectric losses within the medium). We now replace one of the two electrodes with a material of higher resistivity (figure 1), connected to the driving potential at only one end. The resistance of this layer, combined with the reactive (capacitive) impedance of the liquid crystal enables the equivalent circuit of the device to be modelled by a series of cascaded RC filters, analogous to an electrical transmission line. The potential difference between the two electrodes therefore decreases as a function of distance across the device. The exact shape of the curve will depend upon the frequency and voltage of the applied potential, with higher frequencies generating sharper curves.

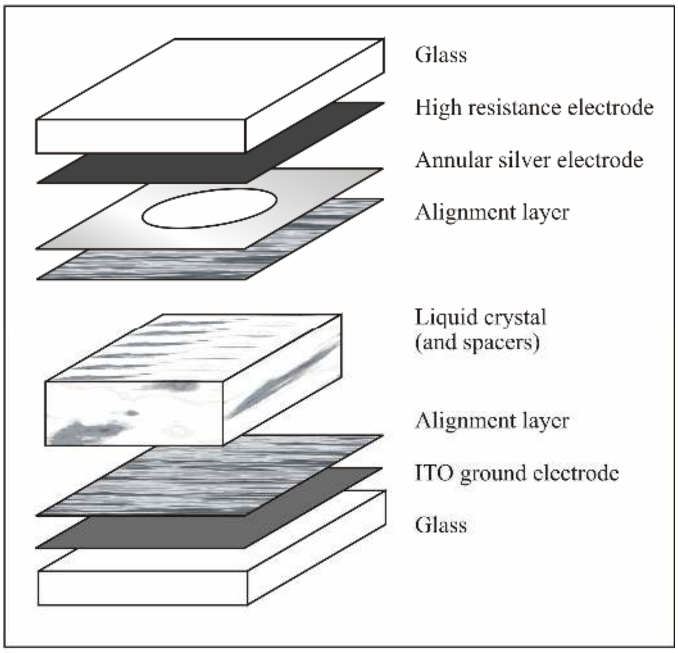

Fig. 4. Structure of the modal liquid crystal lens.

If both ends of the high resistance electrode are connected to the same driving voltage (figure 2) then the resultant potential across the device resembles a quasi-parabolic shape. The resulting phase profile across the device is an inversion of the voltage profile, due to the inverse relationship between voltage and retardance. The exact shape of the function is, in general, non-parabolic. However, careful control of the applied voltage and frequency can give a quasi-parabolic phase profile, similar to that required to generate a cylindrical lens. If we extend this idea further, into an extra dimension, and connect the high resistance layer to the driving potential using an annular electrode (figure 3), then the result is a bowl-shaped electrical potential, and a phase profile that is similar to a spherical lens.

The structure of a modal lens is shown in figure 4, and consists of several thin layers sandwiched between two glass substrates. On the upper side there is a transparent high resistance (0.1 to 1 MΩ/□) electrode with an annular metallic contact. On the opposite side of the liquid crystal cell is the low resistance (1 to 10 Ω/□) ground electrode, also transparent, made from

ITO. The two substrates are held apart by spacers to provide a uniform separation into which liquid crystal is filled. Thin polymer alignment layers provide the liquid crystal molecules with a direction with which to align whilst zero field is applied across the device.

3. EXPERIMENTAL

As described in figure 4, modally addressed liquid crystal lenses consist of a multilayered sandwich structure, based upon two glass substrates. The two substrates are first coated with their respective electrodes and alignment layers. They are then glued together, with spacers providing a narrow cavity between the substrates into which the liquid crystal can be filled. In order to minimise contamination from dust particles, the following fabrication steps are all performed within a class 100 clean-room facility.

3.1 Low resistance ground electrode

The simpler substrate is the ground electrode substrate. A thin layer (10 nm) of indium tin oxide (ITO) is deposited onto 0.7 mm thick glass rectangles (20 mm x 10 mm). This ITO-coated glass, supplied by Merck, has a low electrical resistance (approximately 550 Ω/□). It is then cleaned in isopropanol (IPA) before an alignment layer is deposited.

The polyimide “Liquicoat ZLI 2650” (Merck) was chosen as our alignment layer. It was deposited using spin-coating techniques and baked according to manufacturer’s instructions. Once it has cooled to room temperature, the polyimide layer is gently rubbed with a silk cloth to induce alignment in the polymer chains, and to provide a ‘micro-groove’ structure in the surface of the polyimide to which the liquid crystals will align. This completes the manufacture of the ground electrode substrate.

3.2 High resistance control electrode

The second, control electrode is slightly more complex in structure, but is also based upon a 20 mm x 10 mm glass substrate (approximate thickness, 1 mm). The first layer deposited onto the glass is a high resistance layer. This layer needs to have a resistivity several orders of magnitude greater than that of the low resistance ground electrode. A very thin layer of ITO was therefore sputtered onto the glass (supplied by Thin Film Devices Inc.), providing electrical surface resistance of between 1 and 10 MΩ/□. Alternative high resistance glass coatings have also been tried, including the conductive polymer formulation Baytron CPP 105D (HC Starck), often referred to as PEDOT. Initial testing shows promising results for the conductive polymer and are being investigated further. However, the results presented in this paper refer only to lenses made using high resistance ITO coatings on the control electrode.

Once the high resistance ITO coating has been deposited onto the glass substrate, it is first cleaned with IPA before a thin metallic layer of silver (10 to 100 nm) is evaporated on top of the ITO, using an Edwards evaporator. During the deposition, a mask is used to produce a 7 mm diameter circle in the centre of the substrate where no silver is deposited. This silver layer acts as an annular electrode contact to the high resistance ITO layer. The final layer to be deposited is once again an alignment layer of Liquicoat polyimide. This is spin-coated, baked and rubbed in the same way as described for the ground electrode substrate.

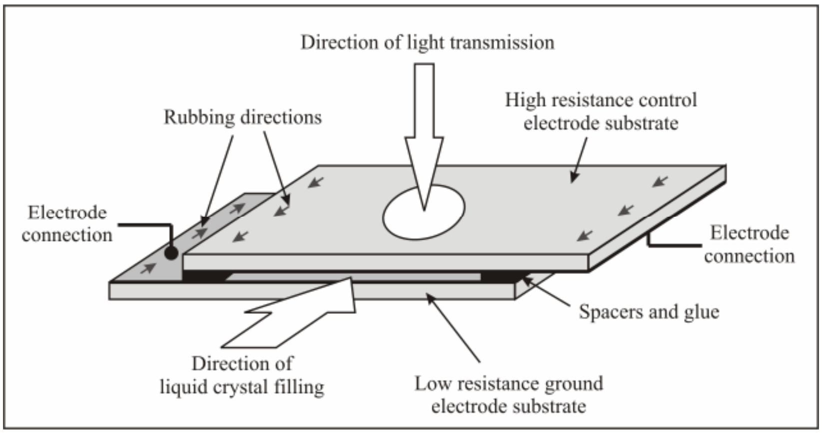

Fig. 5. Diagram showing filling direction, rubbing direction, light transmission and electrode attachments for a modal liquid crystal lens.

3.3 Assembly of the device

Once the two electrode substrates have been fabricated, they are then glued together, and the space between them filled with liquid crystal. A small amount of Loctite UV curable glass adhesive is mixed with spherical, non-conductive, spacer beads (Merck) of diameter 20 μm, and pasted onto the ground electrode along two opposite edges of the substrate. The control electrode is then lowered onto the ground electrode, ensuring that the two polyimide alignment layers are facing each other, and also making sure that the rubbing directions of the two substrates are anti-parallel relative to each other (figure 5). They are also glued together so that they are offset by approximately 2 mm, allowing space for connections to be made to driving electrodes. Once in position, the device is placed under a UV lamp for 10 to 15 minutes to set the glue.

The lenses are now filled with nematic liquid crystal. Earlier devices were filled with the liquid crystal K15 (Merck). In other lenses, the liquid crystal mixture E44 (with 1% C15) (Merck) was chosen because of its large birefringence. The empty lenses are placed on a hot plate, set at around 70 to 80 °C (above the clearing point temperature of the liquid crystal, and are filled with liquid crystal by capillary action.

3.4 Testing of the device

Inspection of the lenses was performed by rotating them between crossed polarisers whilst illuminated by a white light source. Devices were chosen for further testing which showed good alignment, little optical scattering and minimal disclinations or aberrations in the liquid crystal. Wires were then attached to both of the electrodes, which were connected to an Agilent 33120A alternating current signal generator. This provided the necessary sine wave alternating voltage required for driving the lens. Digital photographs of the patterns visible in the lens could then be made, whilst the frequency and applied voltage were varied.

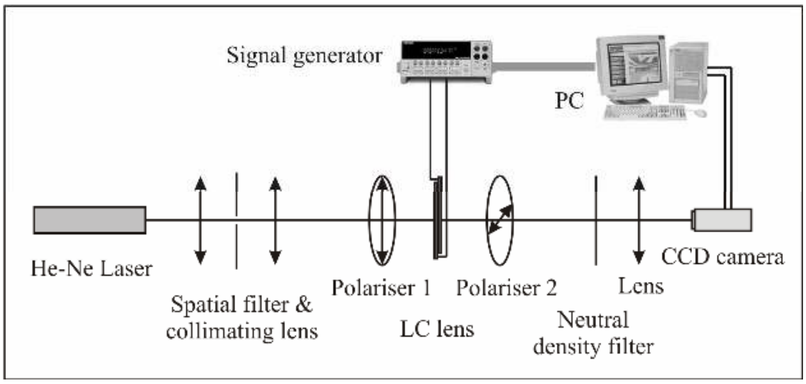

Fig. 6. Experimental arrangement for taking interferograms of working modal liquid crystal lenses.

Optical interferograms of the working lenses were captured using the apparatus shown in figure 6. Collimated light from a red helium-neon laser was passed through a spatial filter and a linear polariser, and then used to illuminate the liquid crystal lens. The transmitted light was then passed through a second polariser (perpendicular to the first), and then reduced in intensity using a neutral density filter before being focussed onto a CCD camera using a standard glass lens. Image capture software allowed interferograms of the lenses to be recorded at various combinations of driving frequency and voltage.

4. RESULTS

Figure 7 shows photographs of a selection of working modal liquid crystal lenses, held between crossed polarisers. (The lenses are illuminated with white light, but the images are converted to greyscale). The images show preliminary, but so far typical results for lenses filled with different liquid crystals. They also illustrate how different combinations of voltage and frequency can be used to generate different strength lenses. Note that it is often possible to generate two near-identical strength lenses using two completely different combinations of voltage and frequency, although one may more closely resemble the ideal parabolic phase profile than the other.

The slightly non-circular appearance of the fringes in the E44-filled lens is a result of an imperfectly circular annular electrode. The evaporation mask used to create the annular electrode had a slightly flat edge at one point along its circumference, which distorts the field profile across the high resistance electrode. Improved engineering of the mask has reduced this problem. Distortions at the far right-hand side of the K15-filled lens are most probably due to use of too much glue, which has accidentally spilled into the lens aperture. Great care must be taken during construction not contaminate the region of the lens aperture. Additionally, non-uniformity in the thickness of the high resistance electrode can cause further distortion of the phase profile. This is especially problematic when dealing with such extremely thin layers of ITO. It is for this reason that alternative materials are being investigated for use as the high resistance electrode layer.

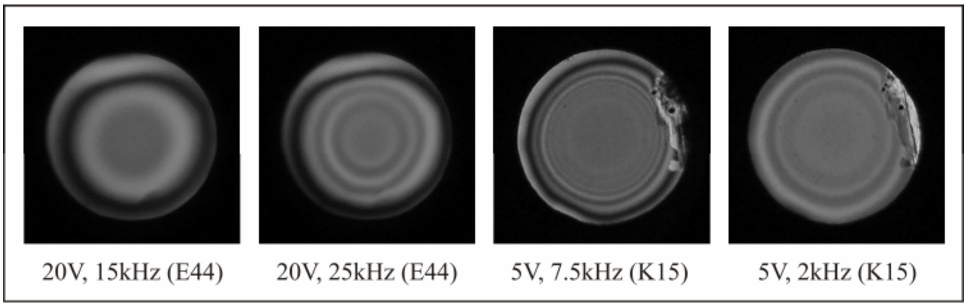

Fig. 7. Photographs of modal liquid crystal lenses, (diameter 7 mm, thickness 20 μm) filled with either E44 (with 1% C15) or K15 liquid crystal, held between crossed polarisers and driven using different voltages and frequencies.

All of the lenses can be set to a position of zero focus (focus at infinity) by applying zero electric potential. However, devices made using larger diameter spacers, and therefore thicker layers of liquid crystal, result in lenses with a wider-ranging (and therefore stronger) focussing ability. This is due to the increase in optical path length through the device, resulting in an increase in the available phase change. A disadvantage of thicker lenses is response time. The time taken for a modal liquid crystal lens to respond to a switch in voltage from a low value to a higher one (ie: from a long focal length to a shorter one), is relatively rapid (typically less than 0.5 seconds). This is because the electric field drives the liquid crystal into position. The switch-on time is also therefore relatively unaffected by changes in the cell's thickness. However, the switch-off time (or time taken to move from a short focal length to a longer one), which is dominated by the interaction strength between the liquid crystal and the alignment layer (and other factors such as liquid crystal viscosity), is increased dramatically when thicker cells are used, often taking 2 or 3 seconds to fully relax in cells as thick as 20 μm. Multiple lens stacking is currently being considered as a solution for increasing lens strength without compromising response time. Stacking of two mutually orthogonal lenses has the additional advantage of being able to use unpolarised light for lensing, rather than only linearly polarised light which must be used when testing a single lens.

A crude estimation of the focal range if these devices can be made by counting the number of concentric fringes that are visible, and thus calculating the total phase change across the radius of the aperture. The maximum possible phase change across the lens is approximately 14π radians, which (combined with a 7 mm diameter lens) corresponds to a focal length of approximately 70 cm.

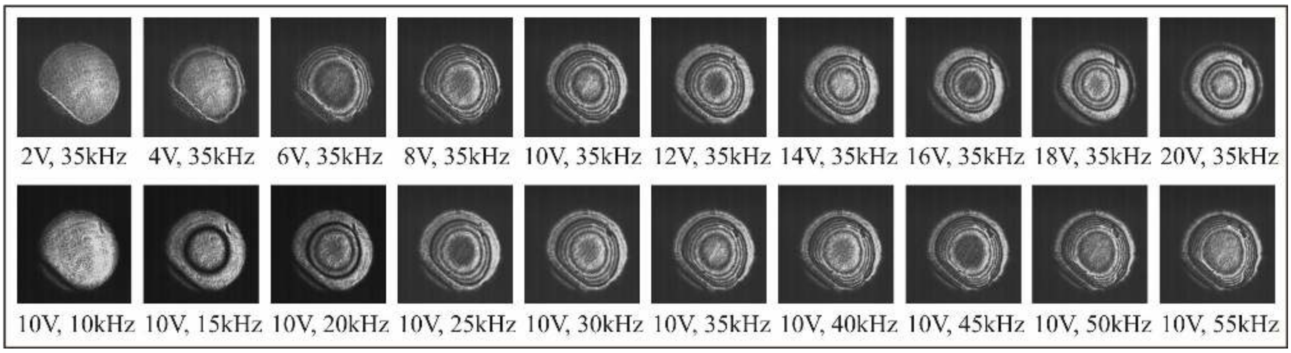

Fig. 8. Interferograms of a modal liquid crystal lens (diameter 7 mm, thickness 20 μm, E44 (1% C15) liquid crystal). The upper row of images shows the trend of increasing applied voltage, whilst the frequency remains constant. The lower row of images is taken at increasing frequencies, whilst held at constant voltage.

Interferograms of a 7 mm diameter, 20 μm thick modal liquid crystal lens are shown in figure 8. The first row of images show how the phase profile of the device varies whilst the applied voltage is incremented gradually from 2 V to 20 V, whilst the frequency is held constant at 35 kHz (an approximately mid-range value for typical operating conditions). At very low applied potentials, the liquid crystal is below its threshold voltage, and there is insufficient field to cause any appreciable lensing. At around 3 V fringes begin to appear as concentric circles around the periphery of the aperture. As the voltage continues to increase, these fringes move inwards, towards the centre, and additional fringes begin to appear around the inside edge. The phase profile becomes more lens-like, and the power of the lens improves with increasing voltage. At higher voltages (approximately 12 V and above for this frequency) the phase profile becomes increasingly distorted. The fringes have now reached the central region of the lens, and the frequency is insufficient to generate the loss necessary to keep the central region at a near-zero potential. The entire phase profile therefore moves upwards in potential, and no further increase in lens power will occur. An aberration is also now visible in the form of an absence of rings towards the edge of the device. The large fields that are now generated in this region result in increasingly smaller phase changes due to the non-linear voltage-phase response of the liquid crystal.

The lower row of images in figure 8 shows the response of the same lens as above as it undergoes an increase in the driving frequency, whilst maintaining a constant potential of 10 V. At very low frequencies the liquid crystal is able to switch with the alternating field, and lensing is not possible. This flickering effect disappears as the frequency is increased, but at 10 kHz and below, there is insufficient dielectric loss across the high resistance electrode for any appreciable lensing to occur. However, as one increases the frequency further, losses in the medium increase, resulting in fringes being produced that are compatible with a lens-like phase profile. At very high frequencies, the dielectric losses can be so large that a ‘bottoming-out’ of the phase profile occurs. The central disc of the interferogram pattern increases in diameter and lens profile moves further away from an ideal parabolic shape.

5. CONCLUSIONS

Preliminary interferogram results for modal liquid crystal lenses have shown that for each applied voltage, there is an optimum driving frequency at which an appropriate lens-like phase profile is generated. Similarly, an optimum frequency exists for each voltage that is applied. Stronger lenses are created by increasing the applied potential, but it is only through careful control of both frequency and voltage that a variable lens of good optical quality can be obtained. The focal range of the lenses is between 70 cm and infinity, and can be increased by making them thicker, but this is at the expense of the switching time between focal positions (typically of the order of 1 second). (Perpendicularly) stacked modal lenses could be used to increase the stroke of the device without affecting response time, and has the additional advantage of being able to work with unpolarised light.

Further work is being carried out investigating alternative materials for use as liquid crystal alignment layers and high resistance electrodes, which will hopefully reduce optical aberrations in the lenses. Control of the thickness (and therefore the resistivity) of the high resistance electrode layer will hopefully also allow fine-tuning of the strength and range of focus that can be achieved. Faster switching is also hopefully possible through the use of dual frequency or polymer network stabilised liquid crystals.

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