Novel switching mode in a vertically aligned liquid crystal contact lens

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Abstract: Liquid crystal (LC) contact lenses are emerging as an exciting technology for vision correction. A homeotropically (vertical) aligned LC lens is reported that offers improved optical quality and simplified construction techniques over previously reported LC contact lens designs. The lens has no polarization dependence in the off state and produces a continuous change in optical power of up to 2.00 ± 0.25 D with a voltage applied. The variation in optical power results from the voltage-induced change in refractive index of the nematic LC layer, from 1.52 to a maximum of 1.72. One device substrate is treated with an alignment layer that is a mixture of planar and homeotropic polyimides, rubbed to induce a preferred director orientation in the switched state. Defects that could occur during switching are thus avoided and the lens exhibits excellent optical quality with a continuous variation in focal power.

OCIS codes: (2303720) Liquid crystal devices; (220.3630) Lenses.

References

1. W. N. Charman, "Restoring accommodation: a dream or an approaching reality?," Ophthalmic and Physiological Optics **25**, 1-6 (2005).
2. H. E. Milton, P. B. Morgan, J. H. Clamp, and H. F. Gleeson, "Electronic liquid crystal contact lenses for the correction of presbyopia," Opt. Express **22**, 8035-8040 (2014).
3. H. E. Milton, H. F. Gleeson, P. B. Morgan, J. W. Goodby, S. Cowling, and J. H. Clamp, "Switchable liquid crystal contact lenses: dynamic vision for the ageing eye," in *SPIE OPTO* (International Society for Optics and Photonics, 2014), pp. 90040H-90040H-90046.
4. S. Sato, "Liquid-Crystal Lens-Cells with Variable Focal Length," Jpn. J. Appl Phys **18**, 1679-1684 (1979).
5. S. Sato, A. Sugiyama and R. Sato, "Variable-Focus Liquid-Crystal Fresnel Lens," Jpn J Appl Phys 2 **24**, L626-L628 (1985).
6. M. Ye, B. Wang, and S. Sato, "Liquid-Crystal Lens with a Focal Length that is Variable in a Wide Range," App. Opt. **43**, 6407-6412 (2004).
7. A. F. Naumov, G. D. Love, M. Y. Loktev, and F. L. Vladimirov, "Control optimization of spherical modal liquid crystal lenses," Opt. Express **4**, 344-352 (1999).
8. G. Li, D. L. Mathine, P. Valley, P. Äyräs, J. N. Haddock, M. S. Giridhar, G. Williby, J. Schwiegerling, G. R. Meredith, B. Kippelen, S. Honkanen, and N. Peyghambarian, "Switchable electro-optic diffractive lens with high efficiency for ophthalmic applications," Proc. National Academy of Sciences **103**, 6100-6104 (2006).
9. T. Scharf, J. Fontannaz, M. Bouvier, and J. Grupp, "An adaptive microlens formed by homeotropic aligned liquid crystal with positive dielectric anisotropy," Mol. Cryst. Liq. Cryst. **331**, 235-243 (1999).
10. A. Y. Gvozdarev, G. Nevskaya and I. Yudin, "Adjustable liquid-crystal microlenses with homeotropic orientation," J. Opt. Tech. C/C OF OPTICHESKII ZHURNAL **68**, 682-686 (2001).
11. J. S. Patel, and K. Rastani, "Electrically controlled polarization-independent liquid-crystal Fresnel lens arrays," Opt. Lett. **16**, 532-534 (1991).

1. Introduction

One of the greatest issues in modern optometry is the correction of presbyopia, the age-related natural deterioration of the accommodation mechanism of the eye. Presbyopia reduces near vision acuity and is difficult to correct with contact lenses; all commercially available correction devices suffer from optical compromises [1]. Liquid crystal (LC) contact lenses have been proposed as an effective solution for correcting presbyopia as the additional lens power needed for near vision can be turned on and off [2, 3]. Such LC lens-based vision correction could replicate the accommodation mechanism of the eye, with none of the visual compromises associated with current technology.

There are many different designs of LC lenses, including lens-shaped LC layers [4, 5], flat gradient index lenses [6,7] and diffractive lenses [8], though most are not appropriate for contact lens implementation. Recent work by Milton *et al.* created switchable LC lenses using contact lens substrate materials and geometries with a non-uniform LC lens layer [2, 3]. The work demonstrated that LC contact lenses are an excellent approach to the correction of presbyopia, with the devices providing a change of +2.00 D across the whole field of vision. In order to create a lens to correct presbyopia, a LC layer with planar alignment and a negative meniscus lens shape was used. Above the LC threshold voltage (V_{th}) the refractive index of the LC layer decreases for light polarized parallel to the director, increasing the optical power of the LC layer and switching the contact lenses by +2.00 D [2].

An alternative mode of operation is proposed here, involving the use of a vertically aligned (homeotropic) nematic LC layer. In a homeotropically aligned LC device, the director is initially perpendicular to the substrates. For a nematic material with negative dielectric anisotropy, the application of a voltage above the material-dependent V_{th} causes the director to begin to align parallel to the surfaces. In such a geometry the refractive index of the LC layer is a minimum in the 'off' state, defined by the ordinary refractive index (n_o); this is polarization-independent, offering a significant advantage over other lens designs. In the 'on' state, the refractive index tends towards a maximum value given by the extraordinary refractive index (n_e) for light polarized parallel to the director (Figure 1).

Homeotropic electro-optic modes have not been explored previously in non-uniform LC layers and reports of electrically switched homeotropically aligned LC lenses are restricted to devices with parallel substrates using gradient index [9, 10] and diffractive geometries [11], neither of which can be readily applied to a contact lens. A glass-based non-parallel homeotropically aligned LC layer has been reported by one group, though the focus change was demonstrated with temperature rather than with an applied voltage [4]. Here, we demonstrate that the homeotropically aligned nematic material MLC-2081, which has negative dielectric anisotropy, can be used in a LC contact lens. The optical power of the lens can be switched continuously through ±2.00 D by voltages of less than $7.1V_{rms}$. We describe methods of achieving high quality homeotropic alignment on curved polymethyl methacrylate (PMMA) devices, and methods of ensuring a uniform director profile in the lens upon switching. We discuss the advantages of the homeotropic geometry, including a polarization independent off-state and simple device construction.

2. Lens Design and Construction

For a contact lens to be placed into the eye, appropriate geometries and materials are required. Here, PMMA substrates are chosen due to their historic link to the contact lens industry and use in previous LC lens designs [2, 3]. Figure 1 illustrates the optics of the device; the LC layer is in the shape of a negative meniscus lens and extremes of the director configuration are indicated. For a contact lens, the base radius of curvature of the device is that of the human cornea (7.8 mm). The basic lens design is as described in previously [2], with the combination of optical powers of the layers defining the total optical power of the device. The nematic LC, MLC-2081, was chosen because of its relatively high birefringence, $\boldsymbol{n_e - n_o = \Delta n = 0.21}$, and dielectric anisotropy, $\boldsymbol{\Delta\varepsilon = -4.2}$ (Values as quoted in the Merck Chemicals Ltd data sheet). Increasing $\boldsymbol{\Delta\varepsilon}$ decreases V_{th} and the high birefringence maximises the range of focusing power while minimizing the thickness and hence response time of the LC layer. A homeotropic layer of MLC-2081 has a refractive index of $\boldsymbol{n_o = 1.52}$ and the lens design is such that the increase in refractive index above V_{th} decreases the optical power of the LC layer (P_{LC}) from –5.50 D to –7.75 D (well above V_{th}). In fact, the LC director is strongly anchored at the lens surfaces with maximum director deformation in the centre, tending towards planar well above V_{th}. Thus the effective refractive index of the LC layer is continuously variable. The optical power of the lower and upper substrates is –0.50 D and +6.25 D respectively, so that the total optical power changes between 0.25 D and –1.75 D.

The layer structure in the device is shown in Fig. 2. The PMMA substrates are lathed using an Optoform 30 contact lens lathe (Sterling, Florida, USA), the inner surfaces coated uniformly by sputtering with transparent Indium Tin Oxide (ITO) electrodes and electrical connections are made using a conductive paint [2]. High quality LC alignment is induced by polyimide alignment layers spin-coated onto the surfaces in intimate contact with the LC layer. The lower (convex) substrate is coated with SE-1211 (Nissan Chemical Industries Ltd., Japan) promoting homeotropic alignment. The upper (concave) substrate is spin-coated with a 1:10 mixture of SE-3510 (Nissan Chemical Industries Ltd., Japan), which promotes planar alignment, and SE-1211. After adding the alignment layers the substrates are baked at 60°C for 2 hours and the upper substrate is then rubbed with a velvet ball in a uniform direction. The baking temperature is much lower than is typical for polyimide alignment layers in glass devices because the PMMA substrates soften at higher temperatures. The SE-1211 layer promotes excellent homeotropic alignment of the LC layer in the absence of an applied voltage. However, the low proportion of SE3510 used in the mix of polyimides on the upper substrate ensures that application of a voltage above V_{th} reorients the LC director towards the unique rubbing direction, parallel to the substrates. Without such treatment, the reorientation could occur in any axial direction of the lens with significant scattering at the boundaries between domains. The quasi-planar geometry in the field-on state means that the maximum change in focusing power is only achieved for light polarized along the rubbing direction. This construction process has several simplifications compared with that for the planar aligned device reported previously. In [2], both substrates had to be rubbed, a technically difficult process especially on the convex surface. Further, the rubbing directions on the two surfaces had to be carefully aligned. In homeotropic alignment, only a single substrate needs to be rubbed, chosen to be the concave surface, which is much easier to rub uniformly.

3. Experimental Methods

The alignment quality of a LC layer can be assessed qualitatively using polarizing microscopy. A DM 2500P polarizing microscope (Leica Microsystems, UK) is used, with the device placed between crossed polarizers. An Agilent 33220A, 20-MHz arbitrary wave form generator (Aglilent, California, USA) supplies the alternating voltage to the LC layer. Polarizing microscopy images of the lenses are recorded using a DeltaPix DP200 camera (DeltaPix, Denmark). The optical and resolving powers of the lenses are determined using the same methods described previously [2]. The apparatus allows characterization of the focal length and point spread function (PSF) of the lenses. An expanded 10 mW 589 nm laser is used as the light source and a BC106-VIS CCD beam profiler (Thorlabs, New Jersey, USA) with a pixel size of 6.47 µm and a capture area of 1360 x 1024 is the detector. A polarizer is included in the optical arrangement before the detector to take account of the polarization dependence of the focusing power of the switched lens. The device described here has negative optical power so a +5.00 D diffraction limited lens is included in the optical arrangement to produce a real focal point. The focal length of the lens is determined from the position of the focal point while analysis of images of the focal point using the beam profiler allows characterization of the point spread function (PSF). The resolving power of the lens, associated with the modulation transfer function (MTF), is calculated from the PSF measurement; the MTF is described in line pairs per milliradian to allow comparison between lenses of different optical powers. The MTF50 values (the cut-off frequency at modulation = 0.5) are used to compare different MTF curves quantitatively. An aperture size of 4 mm is used for all measurements and calculations. All MTFs are deduced from the horizontal cross section of the PSF.

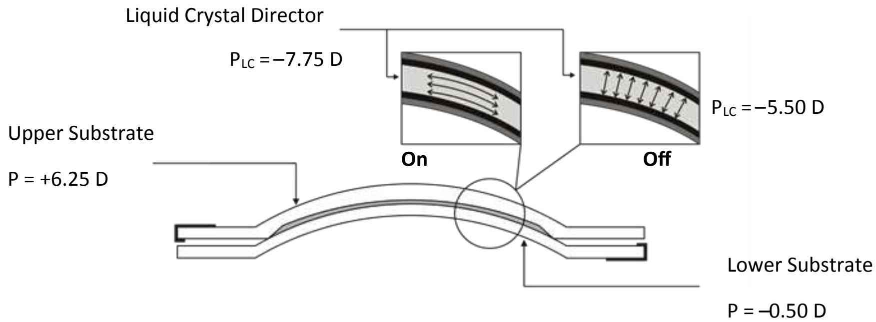

Fig. 1. The optical design of the LC contact lens showing the optical power of each of the layers; the combination forms a system that switches between +0.25 D and –1.75 D. The change in optical power is facilitated by the director reorientation from perpendicular to parallel to the substrates, resulting in a change in refractive index of 1.52 to 1.73.

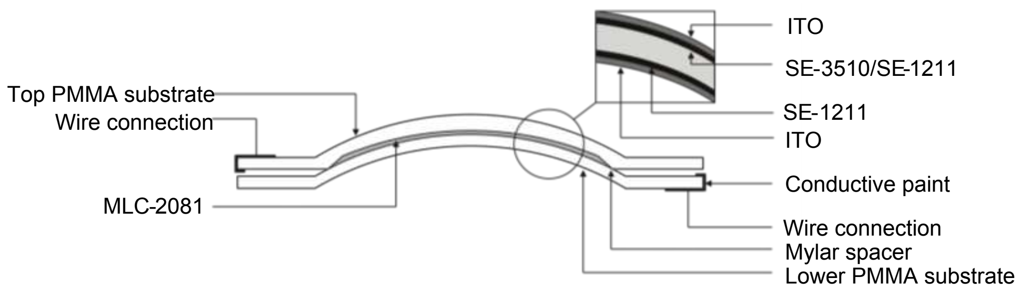

Fig. 2. A schematic of the LC contact lens structure. The insert (not to scale) shows the layers that align the LC and allow voltage application across the LC layer. The 3.6µm thick Mylar spacer electrically insulates the two substrates.

4. Results and Discussion

Polarizing microscopy images of the lens with and without an applied voltage are shown in Fig. 3. The uniform dark texture in Fig. 3 (left) confirms the excellent homeotropic alignment achieved in the lens. The dark state is observed as only n_0 is experienced by the light passing through the device; any non-homeotropic domains have a residual birefringence and would be clearly visible as bright regions. On application of voltages above the V_{th} (Fig. 3 right images), the transmitted light intensity increases and birefringence colors are observed that depend on the effective birefringence and thickness of the LC layer. The uniformity of the LC texture at high voltages is clear, with strong alignment along the rubbing direction and excellent alignment quality. The rubbing of the upper substrate clearly promotes the desired unidirectional LC director in the 'on' state, removing the potential degeneracy.

The LC contact lens can provide a variation in focal power of up to –2.00 ± 0.25 D, Fig. 4. V_{th} is measured to be 2.1 V_{rms} (Figs. 3 and 4), in excellent agreement with the calculated value of 2.2 V_{rms} deduced using $V_{th} = \pi\sqrt{k_{33}/\varepsilon_0|\Delta\varepsilon|}$. k_{33} is the splay elastic constant of the material (determined to be 19.2×10^{-12} N in a separate experiment) and ε_0 is the permittivity of free space. The focal power is measured to be –0.25 ± 0.25 below V_{th}, varying continuously with increasing voltage to a limit of –2.25 ± 0.25 D. Calculations of the expected optical power made using the thick lens equation give values below and above V_{th} of +0.25 D and –

1.75 D respectively, in good agreement with the experimental values. The small absolute difference in optical power of –0.50 D between the experiment and the calculation is attributed to slight deformations in the flexible substrates caused by the fabrication process. The excellent optical quality of the lenses is seen in the images inset to Fig. 4 where the lens is used with a DSLR camera lens that brings text into focus for each applied voltage.

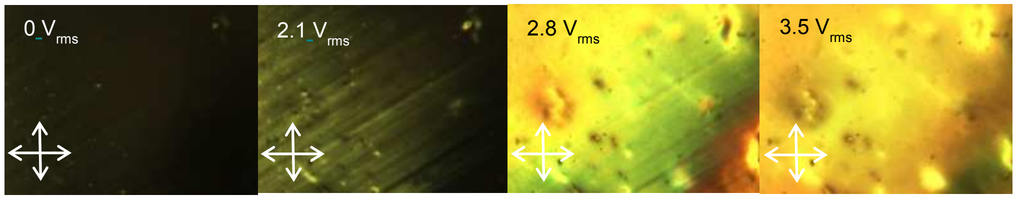

Fig. 3. Polarizing microscopy of the LC lens, illustrating the quality of alignment and switching behavior (100x magnification). The dark state at 0 V_{rms} indicates excellent homeotropic alignment, with bright when the lens is switched. The rubbing direction at 45° to the crossed polarizing axes (white) can be observed in the middle images.

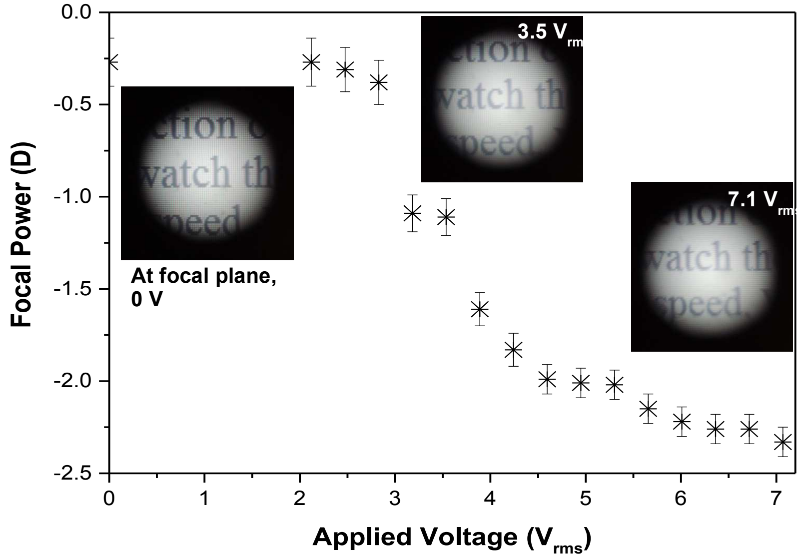

Fig. 4. The focal power as a function of applied voltage. V_{th} is at ~2 V_{rms} and the focal power from –0.25 D in the off state, tending towards –2.25 D at 7.1 V_{rms}. The images show the excellent optical quality of the LC lens.

The optical quality of the lenses is quantified by the PSF and MTF of the devices. Measurements were carried out over a range of applied voltages and the lens quality was monitored as the focal length was varied. Fig. 5 compares the measured resolving power of the lens at different voltages, the two PMMA substrates and a calculated diffraction limited lens. The MTF curves of the LC contact lens at 0 V_{rms} and 5.7 V_{rms} indicate comparable resolving powers, with MTF50 values of 1.39 and 1.00 line pairs/mrad respectively. Indeed, the resolving power of the lens is comparable to that of the PMMA substrates (MTF50 values are 1.84 and 1.25 line pairs/mrad). The calculated MTF50 for a diffraction-limited system is 3.17 line pairs/mrad. We can conclude that the LC lens element does not significantly affect the quality and hence the resolving power of the contact lens.

The response time of the planar aligned LC contact lens was ~3 seconds [2], similar to that of a parallel nematic LC device of equivalent thickness. The response time of a homeotropic device is given by $\tau_{on} = \eta d^2/(\varepsilon_0 \Delta\varepsilon V^2 - k_{33}\pi^2)$, where η is the liquid crystal viscosity (η = 0.4 Pa s for MLC-2081), d is the thickness of the LC layer (d = 50 μm in the center of the device and 67 μm at the outer edge) and V is the applied voltage. The switching time calculated for a 50 μm thick homeotropic device containing MLC-2081 with an applied voltage of 5.7 V_{rms} is ~ 1 second, of the same order as the experimentally determined switching time of 2.1 ± 0.25 seconds. A number of approaches can be taken to reduce the response time including minimizing the LC layer thickness, increasing the driving voltage and optimization of the LC by reducing the viscosity and increasing dielectric anisotropy.

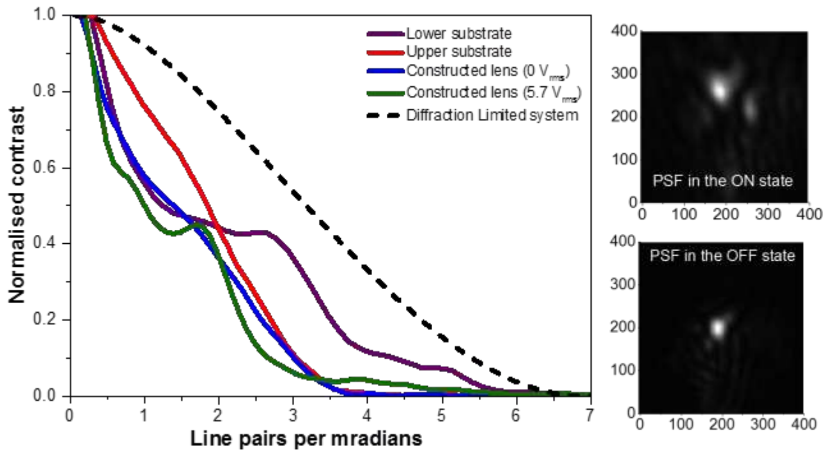

Fig. 5. MTF curves of the LC contact lens and its component substrates compared with a diffraction limited lens. MTF50 values of 1.39 and 1.00 line pairs/mrad are found for the LC contact lens at 0 V and 5.7 V_{rms} respectively. MTF50 values of 1.84 and 1.25 line pairs/mrad are measured for the upper and lower substrates respectively and the MTF50 calculated for a diffraction limited system is 3.17 line pairs/mrad. The PSFs of two states are on the right.

5. Conclusions

A LC lens utilizing homeotropic alignment and thus a new switching mode has been developed. The materials and geometries used are appropriate for contact lens use. The nematic LC layer takes the shape of a negative meniscus lens and upon activation, provides a continuous change in focal power up to –2.00 D. The optical quality of the lens appears to be limited by the quality of the PMMA substrates. The use of the homeotropic switching mode offers several advantages over other lens geometries, including simpler construction techniques and polarization-independent focusing in the 'off' state. The alignment treatment used in the lens allows control of the director during switching, removing degeneracy of the director orientation and hence avoiding defects that would otherwise occur during switching. Such defects would significantly reduce the optical quality of the lens and it is this director control during switching that ensures both excellent optical quality at all voltages and the continuous change in optical power achieved with this lens. Other LC lens geometries can easily be suggested. For example the homeotropic LC layer could be in the form of a positive meniscus lens and the substrates designed to have negative optical power. Then the 'off' state has zero optical power and a switch of +2.00 D would be induced at high voltages, ideal for the correction of presbyopia. Our homeotropic LC lenses are well-placed to take advantage of new materials and fabrication developments to provide fast, high quality vision correction.

Acknowledgments

We are grateful to the UK DIFD, the EPSRC (EP/L015188/1) and UltraVision CLPL for funding. The authors thank J Clamp for the PMMA substrates, Prof. J W Goodby and Dr. S Cowling for the MLC-2081 and Dr V Nouritt for help with the PSF and MTF measurements.