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Polarisation Independent Liquid Crystal Lenses using Embossed Reactive Mesogens

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Abstract

Liquid crystal lenses have promise in optical systems owing to their tunability combined with low electrical power, cost and weight. A good example of such a system is switchable contact lenses for the correction of age-related presbyopia. Large phase modulation can be done using nematic liquid crystals. However, the birefringent materials are inherently polarisation dependent, usually requiring orthogonal polarisations to be focused separately. A novel method is presented for producing polarisation independent lenses based on reactive mesogens.

Author Keywords

Liquid crystal lens; Switchable Contact Lens; Nematic; Reactive Mesogens; Embossing; Adaptive Optics.

1. Introduction

The low voltages required to modulate the phase of nematic liquid crystals has long suggested their use for adaptive optical elements, such as switchable gratings, prisms and lenses [1]. Many types of lens have been suggested [2], including both refractive and diffractive types, where the variation of phase is induced through changes of shape, electric field or alignment of the liquid crystal director. Nematic liquid crystals are birefringent materials, with cylindrical symmetry and a single optic axis. Hence, field induced optical phase changes only occur for light polarised in the plane of the optic axis parallel to the extraordinary refractive index. Light polarised perpendicular to this will experience the same ordinary refractive index regardless of the voltage applied. This is not an issue for the many applications where polarised light is used, for example to provide different images for the left and right eye. However, for switchable contact lenses [3 - 6] and camera lenses [7], it is important that lenses operate with unpolarised light and with high efficiency.

The simplest adaptive contact lens uses a nematic liquid crystal contained within an electrically cavity with a varying thickness Δd to form a meniscus lens, as shown in Figure 1 [3 ,4]. The refractive index of the lens substrate is matched to the ordinary index of the liquid crystal so that there is no lens effect for the vertical state, whereas in the horizontal state light polarised parallel to the extraordinary index is not matched and lensing of focusing strength ΔP occurs. A variety of arrangements are possible [6], such as the homeotropically-aligned version with a negative $\Delta\varepsilon$ nematic material [4] shown in Figure 1. For typical LC with $\Delta n \approx 0.25$, the change in cavity spacing across the an 8mm diameter contact lens is $\Delta d \approx 25\mu m$ to achieve the typical focal correction of ΔP = 2.0 - 2.5D for presbyopia. Thus, the simple meniscus type is well suited for contact lenses, since

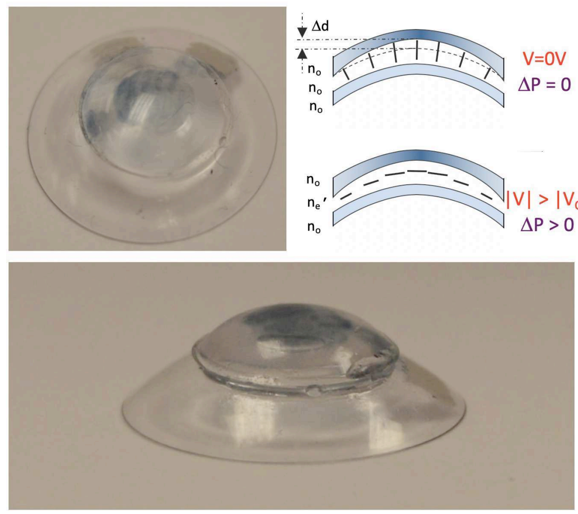

Figure 1. *Switchable Contact Lens using nematic LC from Dynamic Vision Systems [3-6]. There are a variety of potential geometries including the Positive Meniscus Lens arrangement using homeotropically-aligned nematic [4, 5] as shown in the inset.*

the optical response time for nematic of this cell gap is significantly lower than the target correction speed of 1s. This type of lens is currently being used by the UK company Dynamic Vision Systems Ltd (DVS).

An essential requirement for any ophthalmic lens, including contact lenses, is to focus the light independently of polarisation. Previous methods for achieving this insensitivity are shown in Figure 2. The typical method for is to use two orthogonally aligned lenses in series [3, 8, 9], Figure 2a). However, this adds increased optical loss, cost, weight and manufacturing complexity. Alternatively, electric field effects that are inherently polarisation-independent may be used, such as those that occur in cholesteric liquid crystals with helical pitches that selectively reflect in the near-Infrared [10], Figure 2b) or the Kerr effect in Blue-Phase Liquid crystals [11, 12]. However, in addition to being more difficult to align and having higher switching fields, these modes have a fundamentally lower phase modulation, being related to $\Delta n/2$ rather than Δn as for the nematic type. Because the response time increases with square of cell gap, this would lead to almost a four-fold decrease of speed for the cholesteric type, and would prohibit the use of a simple meniscus lens type for contact lenses. Other polarisation independent modes include diffractive lenses with alternating alignment direction in the Fresnel zones [13], Figure 2c). However, the fabrication is rather complex for a contact lens, and the resulting lens is highly chromatic and low efficiency.

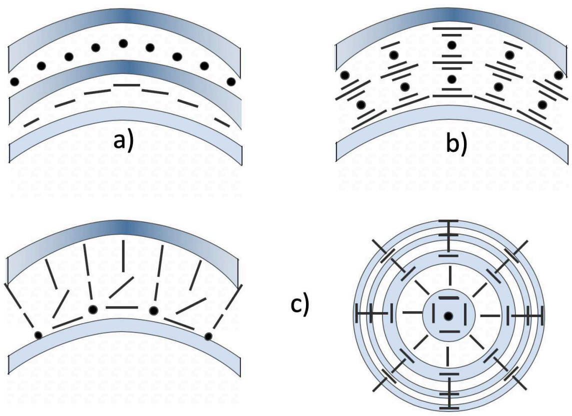

Figure 2. Previous approaches for achieving Polarisation independence: a) Dual chamber; b) NIR Cholesteric or Blue-Phase LC; c) Alternating orthogonally photo-aligned Fresnel Zones.

2. Novel Design for Nematic Polarisation independent Lens

The objective of the present work was to design an arrangement for a conventional nematic liquid crystal that could produce polarisation independent operation for either multi-level diffractive or refractive optical structures, producing high efficiency lenses operating at lower voltages. The approach taken was to form optical structures on the internal sides of the liquid crystal device from birefringent materials that are index matched to the contacting liquid crystal and orthogonal to each other [14]. The quiescent state of the liquid crystal can either be a uniform birefringent waveplate in the half-wave plate condition or, preferably, a 90° twisted nematic arrangement, as shown in Figure 3. The refractive or diffractive lens structures are formed in parallel-aligned reactive mesogen on both internal surfaces of the liquid crystal lens, deposited directly onto the electrodes. The optic axes of the birefringent material are arranged to be orthogonal in both cases, with both refractive indices matched to those of the contacting nematic liquid crystal.

Without applied field, the nematic remains aligned parallel to the lens optic axes and is therefore index matched for any polarisation: lensing does not occur. However, the polarisation state is rotated through 90° due to the TN structure. When the liquid crystal is switched by the applied field, the polarisation conversion stops and the index matching condition is lost for one polarisation at the first surface of incidence, which then exhibits some component of the extraordinary refractive index. The upper lens then focuses this polarisation, but the other is transmitted through the liquid crystal without focussing. When the first polarisation is incident on the lower lens substrate, its polarisation plane is parallel to the ordinary index and no further optical effect occurs. However, the polarisation that was unaffected by the first substrate, now experiences the unmatched refractive index condition, and hence lensing. In this fashion, lensing for orthogonal polarisations occurs separately at the two surfaces.

3. Embossing method of replication in birefringent structures

A simple method for creating birefringent lenses onto the inner surface of an LCD is to use reactive mesogens (RM), Figure 4. The best optical properties and simplest geometry result if the liquid crystal is in direct contact with the RM, so that the liquid crystal aligns with the polymerised director of the RM and no-extra alignment layer is required. This requires the electrodes to be below the passive birefringent element, in the conventional position for an LCD. However, any unwanted offset between the electrodes and the optical structure causes severe electrical losses in the device. This can be minimised using the embossing approach used previously to construct zenithal bistable LCD [15, 16], as shown in Figure 4a).

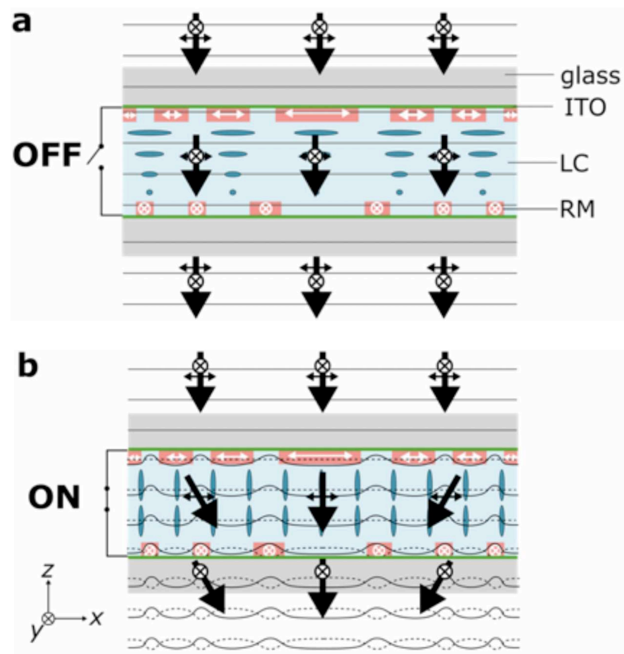

Figure 3. Operating principal of the proposed lens [14]. In this example, a simple two-level diffractive Fresnel lens is shown, though more complex diffractive or refractive structures have also been demonstrated.

The master lens is first defined by conventional methods, including lithography, lathing or moulding. This is copied into a photocurable or thermosetting resin on PET backing film. The resulting inverse lens structure has a surface alignment direction imposed, either through rubbing or photoalignment. The device substrate also has a thin alignment layer deposited onto the ITO electrodes. Uncured RM is placed at one side of the substrate and the film is then pressed onto RM and passed from one side of the device as shown. The highest features of the lens structure touch the alignment layer, with the liquid RM flowing into the gaps that form the lens. In this fashion, the unused RM is pushed ahead of the roller, rather than contributing to offset under the structure. After curing, the RM remains aligned by both the substrate and the surface of the film to give a uniformly birefringent lens.

4. Results for a Polarisation independent Diffractive Fresnel Lens

This method was used to form two and three level Fresnel zone plate structures, with 5mm diameters, and designed for a focal length of 200 mm at a wavelength of 594 nm. The alignment quality for a three-level lens is evident from studying between

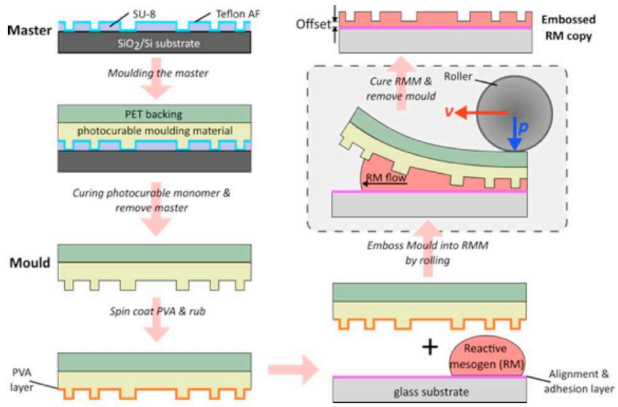

Figure 4. Method of copying the lens onto a backing film and then embossing it onto the ITO coated liquid crystal lens substrate using embossing.

crossed polarisers, as shown in Figure 5. The dark state of Figure 5c) is particularly indicative of the excellent alignment achieved. Results for a two-level diffractive Fresnel lens are shown in Figure 6, where the lens efficiency reached 33% with only 10V applied and regardless of input polarisation state. This is slightly lower than the theoretical 41% maximum for a binary Fresnel lens, which is likely due to imperfections in the director alignment in the higher resolution regions of the lens. Multiple level Fresnel structures enable considerably higher efficiencies to be reached.

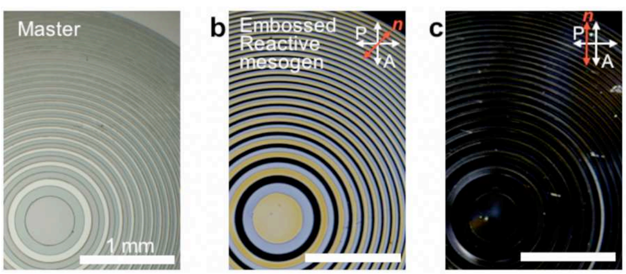

Figure 5. Method of copying the lens onto a backing film and then embossing it onto the ITO coated liquid crystal lens substrate using embossing. b) Master and embossed copy of a 5mm diameter three-level Fresnel lens both at 45° and parallel to crossed polarisers.

5. Impact for use in switchable Contact Lenses

For the design to be suitable for use in contact lenses, the lens structure must be of a refractive type, to avoid chromaticity. For a meniscus contact lens of the design shown in Figure 1, the birefringent refractive lens will have maximum heights of 20μm. Voltage will be dropped across the polymer. However, the cell gap is also set towards the Mauguin limit, where the TN guiding effect is independent of gap. This means that the increase in voltage can be kept small.

6. Conclusions

A simple geometry and fabrication method are proposed that provide superior operation of polarisation independent lenses. This design is applicable to a multitude of optical structures, from switchable gratings and prisms, to high efficiency lenses. In addition to its use in contact lenses, other early adopters for this technology are likely to be adaptive lenses for digital cameras and cell-phones.

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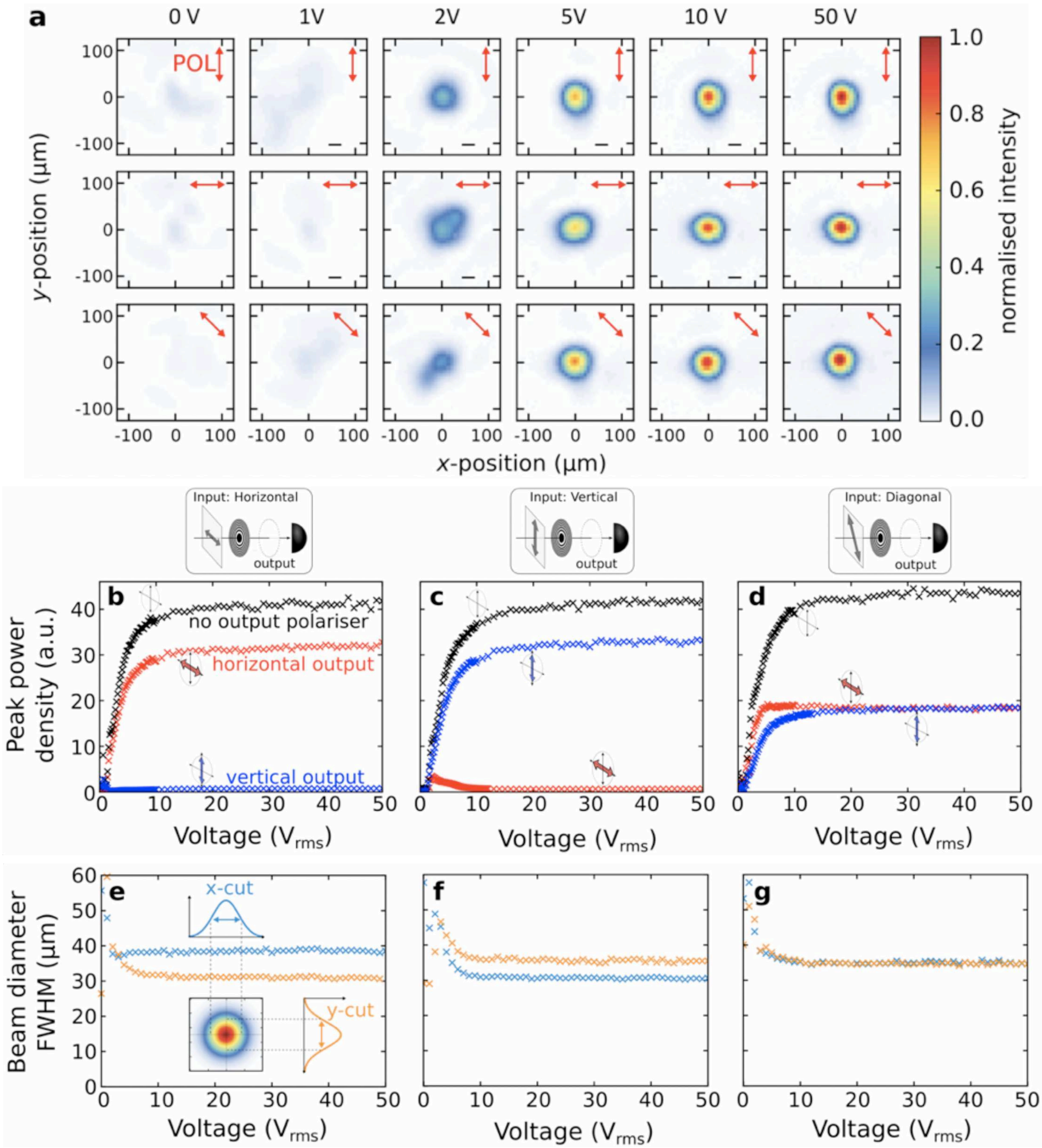

Figure 6. a) Beam profiles measured for different input polarisations (red arrow): vertical, horizontal, diagonal at different voltages. b) to d) Peak intensity of central peak for different input and output polarisations as a function of voltage. e) to f) Voltage-dependent spot diameter (full width at half maximum FWHM) for different input polarisations (no output polariser).