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Liquid crystal contact lenses with graphene electrodes and switchable focus

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ABSTRACT

Presbyopia is a ubiquitous age-related disability of the eye, affecting an estimated 1.04 billion people worldwide, reducing their ability to focus on nearby objects. The various solutions to this inevitable vision deterioration are not compromise-free, with a growing need for approaches beyond conventional spectacles. The research motivation for this work is the unique solution offered by liquid crystal (LC) contact lenses to create compromise-free vision across the whole field of view. The distinctive property of LC lenses is that they are switchable, with the application of a voltage activating the lens. The change in focal power is facilitated via a voltage-dependent change in refractive index of the LC. We have successfully demonstrated several versions of electrically switchable LC contact lenses with variable additional optical power of up to +3.00 D, ideal for the correction of presbyopia.

This paper offers a review of the optical and electro-optical performance recently demonstrated for the different modes of operation realized in nematic systems, including planar (homogeneous) and vertically aligned (homeotropic) aligned devices. The change in optical power obtained depends on the choice of geometry and LC material. A material with higher birefringence allows a thinner LC-lens layer to achieve a particular focal power. In the homeotropic geometry, the refractive index of the LC layer is a minimum in the ‘off’ state (ordinary refractive index, n_o) and the mode is polarization-independent, offering a significant advantage over planar lens designs. The construction is also simplified as only one alignment layer needs to be rubbed. Depending on the geometry used, continuously variable changes in focal power of up to +3.00D have been achieved. The response time of the lenses can be better than half a second, achieved with small applied voltages of $\sim 7V_{rms}$.

A further important stage in the optimization of the contact lenses is the inclusion of graphene as the electrodes. Conventional ITO electrodes are too brittle for these flexible optical systems. The paper also reviews the successful incorporation of graphene into the lenses, with excellent optical and electro-optical results. The device demonstrates the huge potential of graphene in an unconventional liquid crystal device geometry that includes curvature over a relatively large area.

INTRODUCTION

Presbyopia, an inability of the ageing eye to focus on nearby objects is one of the major challenges facing modern optometry. In medical terminology, presbyopia can be defined as the loss of near visual acuity with age due to deterioration in the accommodating power of the crystalline lens. The onset of presbyopia usually occurs between the ages of 40 to 45, with peak occurrence between the ages of 42 and 44 and 100% in people older than 52. An estimated 1.04 billion people were affected worldwide by this impairment of near vision in 2005 which is projected to rise to 1.782 billion by 2050 [1].

The various solutions available to correct near-vision impairment are insufficient and not compromise-free, with a need to look beyond the conventional spectacle glasses. A unique and extremely promising approach is the use of liquid crystal contact lenses that can provide compromise-free vision in the whole field of view. A distinguishing feature of such liquid crystal contact lenses is the ability to provide additional optical power for near vision tasks on application of low voltages (ON state) with the eye able to perform distance vision tasks normally in the OFF state of the contact lens [2-4]. The change in optical power is facilitated by the changing refractive index of the liquid crystal system on application of a voltage and can be continuous, offering mid-distance vision correction. Such an electrically switchable liquid crystal contact lens system offers compromise-free vision, duplicating the accommodation mechanism of the eye, which none of the present day corrections can provide.

In this paper, we review such systems that have successfully demonstrated provision of additional optical power up to +3.0 D to correct presbyopia. We report the electro-optical performance of such contact lens systems in two different modes of liquid crystal geometry; planar (homogeneous) [2, 3] and vertically aligned (homeotropic) [4]. We further describe the optimisation of such systems with the inclusion of graphene electrodes instead of Indium Tin Oxide electrodes (ITO) [5]. These adaptive liquid crystals contact lenses utilize the high electrical conductivity, transparency, flexibility and elasticity of graphene simultaneously incorporated into the curved geometry of the lenses.

LIQUID CRYSTAL GEOMETRY, LENS DESIGN AND CONSTRUCTION

To obtain optimum potential from the liquid crystal material, a defined geometry is a fundamental requirement. The liquid crystal devices are most commonly seen in planar or homeotropic geometries. In case of planar geometry, the liquid crystal director is lying parallel to the two substrates. On the other hand, in a homeotropic geometry, also called the vertically aligned configuration, the liquid crystal director is perpendicular to the two substrates. In this paper, we will report on the development of both these geometries in electrically switchable liquid crystal contact lenses. However, prior to that, it is important to understand the design and construction of the contact lens, which is detailed in the following subsection.

Design and construction of the lens

Both the lens design and geometry of the substrates are important factors in building a successful contact lens. Polymethyl methacrylate (PMMA) substrates have been employed in various lens designs [2-4] mainly due to their historic link with the contact lens industry. The lower PMMA substrate has to been designed with its radius of curvature matching that of the corneal dimensions (typically a 7.8 mm radius of curvature) for optimum placement on the eye. The unique feature of our contact lens design is the balanced optical approach taken, in which the substrates as well as the liquid crystal layer exhibit optical power. This distinct approach allows the liquid crystal contact lens to exhibit positive optical power, which is vital for near vision tasks.

Planar aligned liquid crystal contact lenses

One of the first successfully created electrically switchable liquid crystal contact lenses utilized the planar aligned geometry [2, 3]. Figure 1 shows the design and geometry of the substrates and the liquid crystal layer between them, which dictate the optical power of the complete system. In an unpowered state of the contact lens, the power of the substrates and the extraordinary refractive index (n_e) of the liquid crystal layer define the total optical power of the lens. The total optical power of the lens in the OFF state can be designed to have the optical power needed to correct for distance vision if required. When powered, the liquid crystal orientation tends to be such that the ordinary refractive index (n_o) is exhibited, thereby resulting in a reduction in the power of the whole system. The liquid crystalline material utilized for the lenses fabricated in this geometry was 4-cyano-4'-pentylbiphenyl (5CB), which provides a switch of $\pm\mathbf{2.0}\ \boldsymbol{D}$, perfect to correct presbyopia. The thickness of the liquid crystal layer varies from $\mathbf{50}\boldsymbol{\mu m}$ in the center to $\mathbf{67}\boldsymbol{\mu m}$ at the edges of the contact lens and substrates were $\mathbf{100-150}\ \boldsymbol{\mu m}$ thick. The whole contact lens system was $\boldsymbol{\sim}\mathbf{300}\boldsymbol{\mu m}$ in thickness which is normal for a contact lens device.

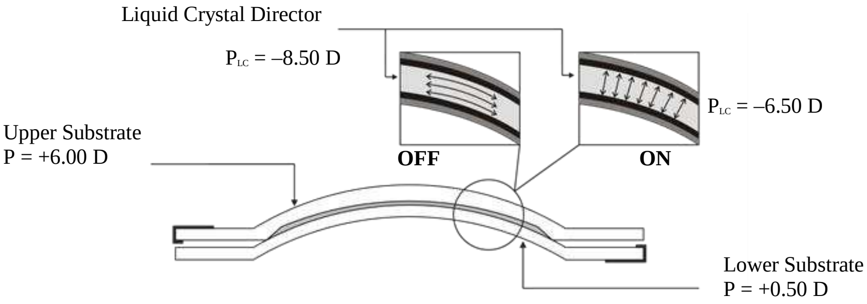

Figure 1. The design and geometry of the planar aligned contact lens. In this case, the two PMMA substrates have positive powers of +6.00 D and +0.50 D; the liquid crystal is 5CB and the LC layer varies the optical power from -8.50 D to -6.50 D on application of a voltage.

The construction of this lens system involved sputtering a layer of ITO ($\sim 20nm$) on both of the PMMA substrates to form the transparent electrodes. Both substrates were then spin coated with a thin layer of poly vinyl alcohol (PVA) which was rubbed unidirectionally to promote planar alignment. The substrates were assembled and insulated via epoxy glue and later filled with the liquid crystal.

Graphene based electrodes in planar aligned liquid crystal contact lenses

The planar aligned geometry was later optimized by using graphene in place of ITO electrodes for ease of manufacturability and potential application to soft contact lenses [5]. In addition to being expensive, the use of ITO leads to various issues such as poor adhesion onto the curved PMMA substrates, non-uniformity and low yields. Moreover, ITO films are brittle and therefore unsuitable for flexible applications. The optical transparency, flexibility, low resistivity, good adhesion and stability of graphene make it a perfect candidate for use in contact lenses. The graphene adheres well to the PMMA substrate and the transmittance through the graphene electrode on the contact lens substrate is comparable to that of ITO. Importantly the flexibility of graphene makes the manufacture of these single contact lens units much easier.

The details of the synthesis of graphene are descried in Ref. [6]. In the constructed lens, graphene with a thin 100nm layer of PMMA was deposited on the lower substrate of the assembled lens (similar to that shown in figure 1). It is to be noted that no alignment layer is needed on the graphene substrate as both PMMA and graphene give good planar alignment. The overall preferred orientation is defined by the rubbing direction on the upper substrate, an approach similar to that used in the graphene-based pixel demonstrated by Blake et al. [7]

In this case of planar alignment, a standard nematic liquid crystal material MLC-6648 exhibiting a positive dielectric anisotropy with a birefringence $\Delta n=0.07$ and relatively a low viscosity was chosen. The lower viscosity of the liquid crystal used led to a system with the additional advantage of a for sub-second response time, which is ideal for a switchable focus contact lens.

Homeotropic aligned liquid crystal contact lenses

Early reports of the homeotropic alignment geometry in liquid crystal lenses was constrained to devices with parallel substrates and gradient index [8, 9] or diffractive lenses [10]. Recently, however, Syed et al. reported such an alignment used in a curved contact lens geometry [4] for the first time. A significant advantage of using such a system is the polarization independence in the unpowered state and the much simpler device construction.

The basic construction of the homeotropic contact lens is very similar to that of the planar (ITO) device described above. The only difference is the use of a polyimide SE-1211 (Nissan Chemical Industries Ltd., Japan) on the lower substrate and a mixture of 1:10 SE-3510 and SE-1211 respectively on the upper substrate. The upper and lower substrates are similar to those shown in figure 1. Further details can be found in Ref. [4]. Unlike the planar aligned contact lens system, only the upper substrate was rubbed, in this case to promote uniform switching on application of a voltage. Rubbing a single substrate simplifies the construction process as compared to the planar device in two ways. Firstly, the upper substrate which is a concave surface is much easier to rub than the convex substrate. Secondly, unlike in the planar device where alignment of the rubbing directions on the two substrates is important, no extra precaution needed to be taken while placing the two substrates together as the second substrate was not rubbed at all.

In the homeotropic device, the nematic liquid crystal, MLC-2081, was selected due to its relatively high birefringence, $\Delta n = 0.21$ and negative dielectric anisotropy, $\Delta\varepsilon = -4.2$. A high Δn increases the range of the optical power change that can be achieved. In an unpowered state, the ordinary refractive index for MLC-2081 is 1.52 which increases on application of voltage towards 1.73. In the lens constructed, the voltage varied the optical power of liquid crystal layer from $-5.50\ D$ to $-7.75\ D$ (well above the threshold voltage, V_{th}). With the optical power of the lower and upper substrates as $-0.50\ D$ and $+6.25\ D$ respectively, the total optical power was seen to vary between $0.25\ D$ and $-1.75\ D$.

RESULTS AND DISCUSSION

All three systems, i.e. planar aligned with ITO electrodes, planar aligned with graphene electrode and homeotropic aligned, were characterized for their optical and electrical properties [2-5]. Polarizing microscopy images of the contact lens revealed the quality of the alignment both for planar [2, 5] and homeotropic geometry. [4] Figure 2 explicitly shows an excellent alignment in case of a homeotropically aligned contact lens at (a) 0 V_{rms} and (b) 3.5 V_{rms}. The dark homeotropic state turns bright birefringent on application of voltage above the threshold voltage, V_{th} $(3.5\ V_{rms})$, demonstrating excellent alignment and switching of the contact lens.

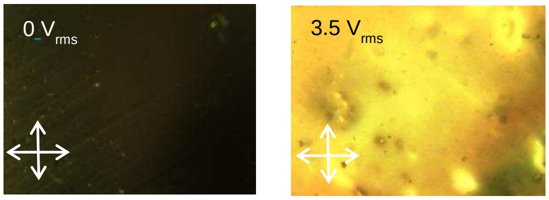

Figure 2. Polarizing microscopy images of the homeotropic contact lens showing excellent quality of alignment. (a) shows the homeotropic state $(0\ V_{rms})$ and (b) the application of $3.5\ V_{rms}$ depicting a quasi homogeneous bright state. The rubbing direction is at 45° to the crossed polarizing axes shown in the lower left corner.

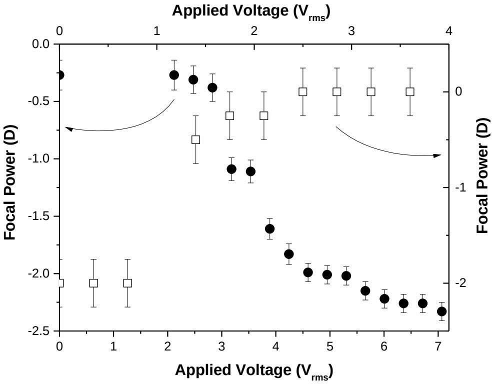

Figure 3. Focal power as a function of applied voltage for planar ITO (open square, top and right axis) and homeotropic (closed circle; bottom and left axis) aligned contact lens.

The focal power of the lens was measured as a function of applied voltage using a method described previously [3]. In case of planar alignment, the total optical power of the contact lens system increased from -2 D to 0 D on application of 3.6 V_{rms} changing by $+2.0 \pm 0.3\ D$ (figure 3; open square, top and right axis). The threshold voltage V_{th} of the contact lens was affected by scattering in this early lens, but is found to be between $0.7 - 1.3\ V_{rms}$. In the planar geometry, a focal power change of +3.0 D was also obtained using a different liquid crystal which exhibited a higher birefringence of 0.32 [3]. In case of the homeotropic contact lens, the total optical power varies from $-0.25 \pm 0.1\ D$ $(0\ V_{rms})$ to $-2.25 \pm 0.1\ D$ $(7.1\ V_{rms})$ on application of voltage (figure 3; bottom and left axis). In case of the planar aligned graphene system, because of the small birefringence of the liquid crystal, a focal power change of $0.7\ D$ is found on the application of voltage. In all the cases, the change in optical power is continuous which is important to address varying optical powers required by different individuals suffering from presbyopia.

The response times of the lenses were found to depend on various factors including the liquid crystal viscosity, the average thickness of the liquid crystal layer, the dielectric anisotropy, the elastic constants and the applied voltage in the same way as conventional liquid crystal devices. The measured response time in case of the planar ITO aligned system with 5CB was ~3 s which reduced to ~2s in case of homeotropic system with MLC-2081 for equivalent thickness and applied voltages. In case of the planar graphene system with the lower viscosity liquid crystal, the response time was found to be ~0.6 s for similar thicknesses and applied voltages. Such a sub-second response time is equivalent to the blink of an eye (a few hundred milliseconds), which is sufficiently fast for this application. Therefore, the choice of the material is highly significant to obtain a faster response time. Further reductions in response time are possible with decrease in the thickness of the device, optimized parameters for viscosity and dielectric anisotropy and increases in driving voltages.

CONCLUSIONS

We have summarized the progress that has been made in developing electrically switchable contact lenses for the correction of presbyopia. We have demonstrated that our approach of a balanced and thin system provides the continuous optical power change, which is ideal for the correction of presbyopia. A geometry that is polarization-independent in the 'off' state is obtained using homeotropic surface alignment. In geometries where there is polarization dependence in either the 'on' or the 'off' state, it is preferable to have the 'off' state polarization-independent; that is the state for normal (distance) vision and a polarization-independent lens focuses all of the incident light, rather than half of it. Novel lens designs that are polarization-independent in both the 'on' and 'off' states are under development. Depending on the choice of the geometry and the liquid crystal material, we can obtain a sub-second response time which is ideal for the dynamic contact-lens application. A question that arises is how the lenses will be powered when on the eye. This is a matter for future development, but it is worth noting that smart lenses with technology that include systems such as built-in sensors are moving from the research environment into use. Such lenses need to be powered and suggested solutions have included induction coils, micro-batteries, or even powering the lens using electrolytes in tears. It seems certain that with the interest in developing such smart contact lens technology, parallel developments in powering will become available.

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