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BRIEF PAPER

Bioplastic tunable liquid crystal lenses for dynamic focus in virtual and augmented reality

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SUMMARY:
We describe a tunable liquid crystal lens based on Fresnel optics that enables variable focus of virtual images displayed by a head-worn VR or AR device. This lens has been fabricated using ultra-thin, light bioplastic film instead of glass, uniquely enhancing visual comfort whilst reducing weight and thickness compared to glass-based approaches.

keywords: *AR/VR; LC Optics; Organic electronics; Tunable lens; Biaxial curvature*

Introduction

Today, most augmented and virtual reality devices have a fixed focus setup (for example, at 2 metres using a 0.5 dioptre fixed lens) and users must accommodate to approximately this distance to comfortably perceive the focused image. Attempting to display virtual content at perceived distances significantly different to the 2m fixed focal length (for example, at 0.5m) can cause visual discomfort associated with vergence accommodation conflict (VAC), which occurs when there's a mismatch between the focal cues for the virtual distance of an object and the fixed plane it is displayed on.

A fixed focal distance is certainly practical for some use cases, such as viewing a virtual monitor at a fixed distance from the user. However, in more dynamic virtual environments it can limit the experience, as rendering of objects at varying focal distance must be avoided – for example, quick changes between interaction with virtual objects within arm's length of the user and those further away. [1].

One way of enabling more focally dynamic virtual objects and environments is to include tunable optics within the device – either as a pair of "push-pull" lenses in AR (one each side of the waveguide), or as a single lens for VR.

Taking the example of a see-through AR device [Fig. 1], a tunable "pull" lens on the pupil-side of the waveguide allows the focal length of a virtual object to be adjusted (by applying -N Dioptres). Since this will also unavoidably change the focal length of the real world, a second lens on the world-side of the waveguide should be included. This "Push" lens is simultaneously driven at an equal and opposite power (+N Dioptres) to the "Pull" lens to return the real world to its original focal length. Hence the combined effect is to control the focal length of the virtual object only.

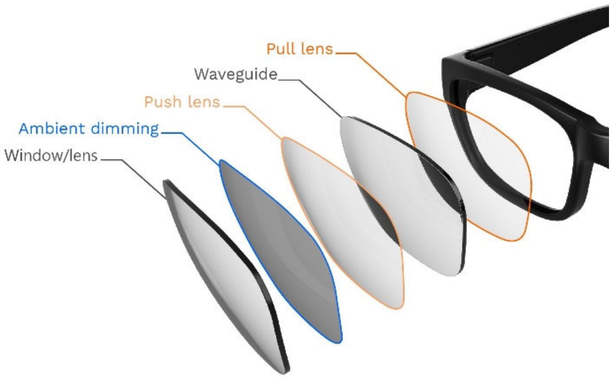

Fig.1 An example simplified push/pull lens stack showing their location in relation to the waveguide in AR glasses

Such an approach could be implemented with traditional glass-based liquid crystal (LC) lenses, such as GRIN (Gradient Index Lens). However, since the approach requires a stack of multiple cells (typically 2 cells per lens, each comprising 2 sheets of glass, meaning 8 sheets in total) - this would add significant glass weight (and thickness) to the optics, and therefore the whole device. A second drawback of glass-based approach is that glass LC cells cannot be biaxially curved, yet such a curvature would allow improved optical and aesthetic enhancements by allowing the active optics to conform to the biaxially curved surfaces of AR and VR optics.

FlexEnable has taken a new approach to the design and manufacture of LC cells, by using a low-temperature manufacturing process and optically ideal bioplastic films instead of glass. With this approach, flexible ultra-thin (<100μm) and ultra-light (<0.25g for an eyeglass size) LC cells can be manufactured. Additionally, the complete fabrication process is undertaken using standard flat-panel display fabrication equipment [2-5].

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Fabricating flexible LC optics

The manufacturing process enables complete LC cells and organic thin film transistors (OTFTs) to be manufactured on tri-acetyl cellulose (TAC) film.

Because both the OTFT and LC cell materials are processable below 100°C, substrates with a low Tg such as TAC film (Tg ~150°C) can be used for active electronics for the first time. TAC film is already commonly used in the display industry, but usually as a substrate for polarizers precisely because of its optical properties (excellent transmission, haze, colour and non-birefringent properties). Until recently, such a material has not been a candidate for active LC optics as the temperatures needed for silicon TFT fabrication (300-400°C) prevent it [6]. Organic TFTs overcome this constraint - any kind of LC cell manufacturable on glass can instead be manufactured on low Tg plastics such as TAC film.

How LC optics differ to conventional fixed optics

In conventional fixed optics, light is focused by the curvature of the lens, and the optical path difference (OPD) across the lens is defined as the product of the fixed refractive index (n) of the lens material and the thickness (d) of the material, which varies as a function of radius. Conversely, in a LC-based GRIN lens, the thickness of the lens (d) is fixed and the refractive index (n) varies as a function of radius, which is achieved by applying a voltage to the birefringent liquid crystal. The optical path difference is therefore d*Δn instead of Δd*n [Fig.2].

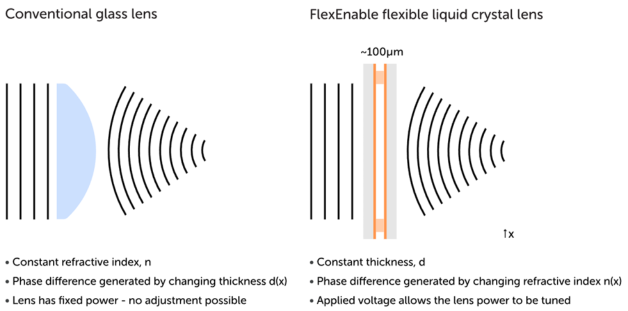

Fig 2. Comparison of conventional and LC lenses

The change in OPD for a GRIN lens of a given cell gap is determined by delta n, which is an intrinsic property of the selected LC material, and typically lies in the range 0.2 to 0.3. for larger diameter LC lenses where large effective OPD is required, phase resets (analogous to a fixed Fresnel lens) are designed into the LC lens using a suitable electrode design, resulting in a Fresnel LC lens.

Lens structure

The LC lens is fabricated with separate top and bottom plates - the bottom plate consists of TAC film with patterned metal buslines. Figure 3 shows a cross section of the structure used to make a Fresnel LC lens [7,8].

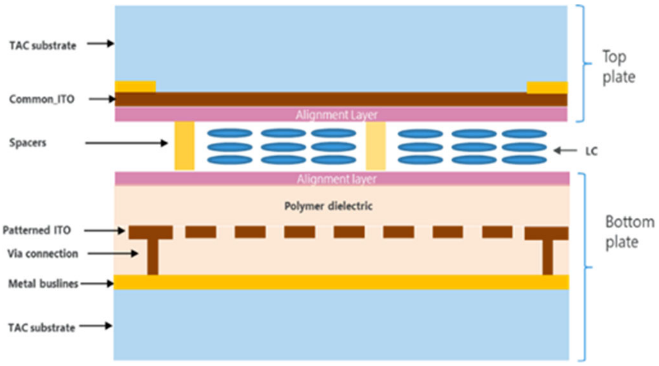

Fig. 3 LC Fresnel lens cell cross section

The structure is patterned on an ITO transparent electrode layer sandwiched between two organic insulator layers. The bottom layer protects against shorting to the metal bus line, while the top layer spreads the field affecting the LC. The final step is to coat a photalignment layer (rubbed alignment layer could also have been used). The top plate is fabricated in a similar way but with less complexity due to the absence of a patterned electrode. Both plates are then brought together to form a cell with the LC layer in-between, using an “ODF” process that is essentially identical to that used for a glass liquid crystal display cell assembly. The choice of cell gap to be used with a given liquid crystal for a given aperture is determined principally by the required lens power, switching speed and MTF, for which there is a trade-off: Reducing the cell gap increases the switching speed, but reduces the lens power. This can be mitigated in the electrode design by increasing the number of phase resets, with a corresponding reduction in lens MTF.

In this work the cell gap used was 10 microns across a 20mm aperture. The resulting optimized single cell structure can focus polarized light; to focus unpolarized light, a second lens with orthogonal alignment layers is required in a stack.

Prototype lens design

For the prototype, two cells of this type, but with orthogonal alignment layer directions, were laminated together to form an orthogonal pair as illustrated in Figure 4. This increased the module thickness to around 250 µm including OCA.

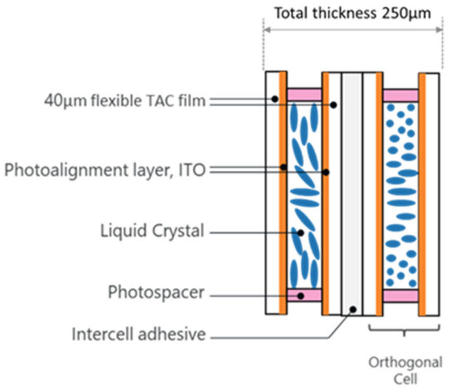

Fig. 4 Cross section of orthogonal cell pair

The lens was designed with an aperture of 20mm and used a cell gap on 10 microns. An electronically controlled birefringence (ECB) nematic liquid crystal was used as the active layer. The substrate used was TAC film at 40 microns thick. Figure 5 shows the final fabricated lens.

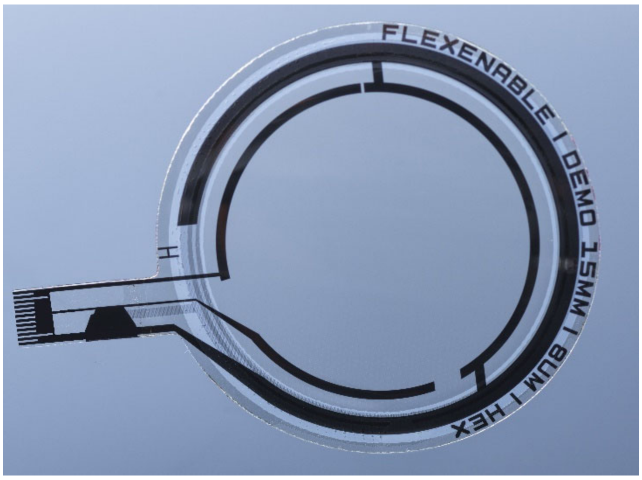

Fig. 5 Final prototype lens

Measuring performance

The focusing ability of the lens was tested using a simple imaging chart and camera system. The Modulation Transfer Function (MTF) was measured and produced a result of > 0.4 at 30 cycles/degree.

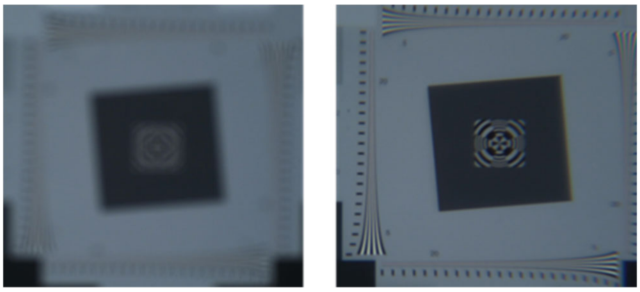

Fig. 6 View through the lens in the off (left) and on (right) states

Figure 6 shows two views of the test chart taken with a camera looking through the lens. The RHS image is in focus when the maximum voltage (5V RMS) is applied to the lens (corresponding to a tunable lens power of 0.25D in the "ON" state). The left-hand image shows the exact same optical setup but with no power applied to the lens (corresponding to a tunable lens power of 0D in the "OFF" state) and therefore showing a dynamic range for the tunable lens alone of 0.25D.

Some chromatic aberrations can be seen in the outer parts of the image (Fig 6 RHS), which are caused by wavelength dispersion. There are several ways this can be mitigated in an overall system when combined with other optics.

Even the relatively modest lens power demonstrated herein is close to useful levels for reducing impact of VAC. In addition, the switching speed (<1sec) and continuous tunability between low and high-power optical states are attractive propositions for designers seeking lightweight and flexible tunable optics.

Both the lens diameter and optical power can be increased by modifying the design. It should be noted that increasing either attribute would require either more Fresnel zones or a thicker cell gap, and the resulting impact on lens quality should be carefully considered.

Discussion, summary

A polarization-independent tunable bioplastic LC lens was fabricated in a total package ~250 microns thick and weighing less than 0.3g. This proof-of-concept has a large aperture (20mm) and ample optical power (0.25D) to reduce VAC.

The low-temperature manufacturing process allows a low Tg bioplastic substrate (TAC) to be used, which ensures the resulting cells are extremely thin and light, easy to stack and can easily be profiled to the required shape using laser cutting. In a previous paper, we have shown that TAC-based LC cells can also be biaxially thermoformed, which makes them especially well-suited for optical applications [9].

There are several avenues for improving the performance of this platform, and we are in the process of building and evaluating enhanced versions with higher lens power for large apertures (>30mm) and increased image quality (MTF, Haze), whilst maintaining the ultra-thin, light form factor. This will enable powerful thin, flexible, lightweight and 3D curvable AR and VR optics that bring greater visual and physical comfort for users and increased product design flexibility for OEMs.

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