

Next Generation Material for Head-Mounted Devices

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ABSTRACT

The recent drive towards high performance Augmented Reality (AR) and Virtual Reality (VR) headsets has generated a new demand for materials designed for the specific requirements of this technology. This paper will present the challenges and status of new materials designed for this application. Materials for both passive and active components will be discussed.

1 Introduction

AR Head Mounted Devices basically consist of a light engine and a means of translating the image generated so that the viewer sees the virtual image as well the real world under all ambient lighting conditions. The goal of this paper is to introduce new materials designed to meet the requirement of engineers designing these devices.

2 RM for AR/VR applications

Reactive mesogens (RMs) are polymerizable liquid crystals. RMs can be aligned using standard alignment techniques for LCs, however they can polymerize into a durable, micron-thin, plastic film upon irradiation with UV light. RMs have been widely used to improve the viewing angle of LC as well as OLED displays as part of an achromatic circular polarizer layer to improve their contrast.

Planar aligned RM films, known as +A films, can be used to manufacture polarization gratings (otherwise known as Pancharatnam Berry (PB) phase gratings) and lenses which have very high diffraction efficiency (D.E.) and are useful components in AR/VR devices. The most popular process of producing these films involves using polarization holography to write a continuously varying pattern into a photo aligning layer which is then used to align a RM layer to produce a periodic birefringent film. To optimize the performance of the polarization grating or lens depending on the intended application, the ones most often considered are birefringence and pitch of the RM material, the total retardation of the film and the minimum in-plane pitch of the periodic structure.

To prepare highly efficient, but also achromatic components, more complicated multi-layered structures

have been proposed and developed [1,2]. Fortunately, the second layer of a properly formulated RM mixture can be aligned on top of the first layer, so the complicated writing process only needs to be done once. Overall writing and coating process is shown in Fig. 1.



Fig. 1 Process of preparing a polarization grating optical element. PAL is the photoalignment layer

RM formulations that can be used to produce such complicated components must have the capability of delivering a suitably durable and stable well aligned film whilst also being capable of being overcoated. The main challenge in designing such formulations are wettability and alignment quality. The following sub-sections discuss these challenges in some detail.

In this work, a thin layer of photoalignment material such as SD1 is spin coating onto a clean glass substrate to prepare PB gratings. Two orthogonal circularly polarized laser beams were interfered on the sample plane, producing a PB continuously rotating polarization pattern. An optimized formulation was coated onto this substrate at a desired thickness to obtain a half-wave plate at 532nm. The sample is then cured at optimum UV dosage. D.E. was measured using 532nm laser.

For the more intricate multi-coating design, first the thickness of each layer is optimized to obtain a half-wave for a complete stack. The annealing of subsequent layers is carried out at a lower temp. to avoid dewetting issues when the film is overcoated.

2.1 Alignment

As the in-plane pitch gets shorter, the alignment becomes more difficult. The issue can be considered as a competition between two distortion energies, the one imposed by the PB surface alignment pitch and the one associated with an undesirable out-of-plane tilt.

In the centre of a layer having an excessively short PB pitch (Λ), tilt of the director can reduce the elastic energy associated with the in-plane splay/bend distortion of the

PB pattern. This tilt comes at the expense of a different, through-layer distortion and elastic energy term. In thick layers of short-pitch PB gratings, the distortion which occurs quantitatively corresponds to a zero-voltage Fredericksz transition. The critical field is paralleled by a critical rate of twist when the thickness of the film exceeds the in-plane pitch of the PB grating. At still short grating pitch lengths, tilt of the director lowers the overall elastic energy and out-of-plane tilt is then inevitable [3]. This is conceptually drawn in Fig. 2. In the typical case where the RM layer is aligned by surface forces only at the lower substrate, this tilt distortion will be all the more likely. Any forces which promote planarity of the director will tend to reduce the possibility of defect formation.



Fig. 2 The consequence of reducing the PB pitch, Λ on the director orientation when viewed in the z-direction

Even below the critical layer thickness, out-of-plane alignment defects are made more probable and are often observed as reverse tilt disclinations (RTDs). Typical examples are shown in Fig. 3. By introducing a twist in the z-direction by adding a chiral dopant to the A-plate RM formulation, the probability of achieving good alignment for a given thickness and pitch increases significantly.



Fig. 3 Microscopic image (10X) magnification showing RTDs in a 1-layer PB grating ($\Lambda = 1.6\mu\text{m}$; $\Delta n=0.18$)

2.2 Overcoating

For reasons of maintaining good alignment or for the purpose of optimizing the optical properties of the PB component, it is often desirable to overcoat one RM layer on top of another one. In the case of well formulated RM mixtures, it is possible to align most planar orientated RM films such as A-plates, twisted A-plates, cholesteric RM films on top of each other. The number of possible combinations of films becomes very large. There are various challenges in preparing PB gratings which could comprise of a single layer or multiple layer stack.

In this work, the effect of the number of layers constituting a PB grating is studied on its alignment and diffraction efficiency. In addition, the effect of varied birefringence (0.18 and 0.24) is also studied here. Two half-wave PB gratings are prepared each for a single and multi-layer stack for $\Delta n=0.18$ mixture. Similarly, for

$\Delta n=0.24$ mixture, three half-wave PB gratings are prepared each for a single and multi-layer stack.

Table 1 shows the D.E. results when two achiral mixtures with different Δn are used in the PB gratings as a single and multi-layer (double stack). The D.E. is defined as $\frac{P_{Tr1}}{P_{Tr}}$ (1st order D.E. with respect to total input transmitted beam power).

Table 1 1st order D.E. (at 532nm) for two different Δn mixtures as a single and double layer PB grating stack

Δn	Stack	Diffraction Efficiency (%)			
		Film1	Film 2	Film 3	Avg.
0.18	Single	93.8	92.7	-	93.2
	Multi	95.8	97.0	-	96.4
0.24	Single	93.3	94.6	95.2	94.4
	Multi	96.1	97.2	98.0	97.1

For both 0.18 and 0.24 Δn PB gratings, the D.E. is higher for a multi-stack (double layer) than in case of a single layer. The 1st order D.E. is higher for multi-layer stack (avg: 96.4%) for both films with $\Delta n=0.18$. Similarly, for $\Delta n=0.24$, all three measured films showed a higher 1st order D.E. for multi-layer stack (avg 97.1%) than the single layer stack (avg: 94.4%). The difference in the various sets is attributed to dust, inhomogeneity in alignment, thickness variation. It is worth noting that both single and double-layer gratings exhibited similar retardation within error.

In another set of experiments, mixture with $\Delta n=0.24$ was used to understand the optimum optical performance using a single or a multi-layer stack. Fig. 4 shows the 1st order D.E. vs average retardation of the respective PB gratings for a single and multi-layer stack. It is observed that both 2- and 3-layer stacks exhibit a higher D.E. as compared to a single layer at values lower and higher than the half wave condition (266nm).

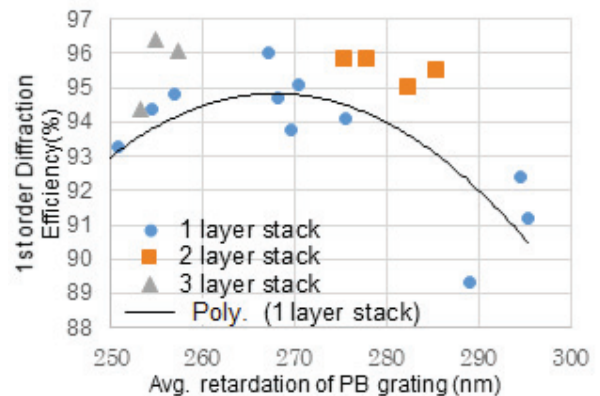


Fig. 4 1st order D.E. (at 532nm) as a function of avg. retardation of PB grating stack ($\Lambda=11\mu\text{m}$).

It is worth noting that the D.E. decreases for a single layer as the avg. retardation value deviates from 266nm. We believe that this interesting result shows that an optimum retardation value along with the number of layers is required to obtain the highest D.E. One of the

reasons for the observed higher D.E. in case of multi-layer stack could be the dependence of alignment quality on the film thickness of the coated layers which make up the PB grating. The films are thicker for a single layer than for a double/triple layer stack which could result in a lower D.E. The multi-layer stack PB gratings exhibit better alignment throughout the PB grating thickness due to thin film thickness for each sub-layer (Fig. 5a).

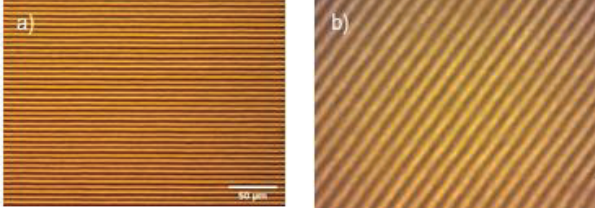


Fig. 5 Microscopic image of a PB grating, a) 2-layer PB stack grating ($\Lambda=11\mu\text{m}$) using 0.24 Δn mixture (10X), b) through a $\frac{1}{4}$ wave plate (20x)

In order words, there is strong anchoring for the coating closer to the substrate and the overcoated layer follows the strong anchoring behaviour at the top of lower layer. On the other hand, the anchoring gets weaker in case of a single thick layer of PB grating. We also observe a small but repeatable improvement in efficiency using the higher birefringent material which again uses thinner coated layers. However, it is an interesting but provisional result which is worth a detailed study.

2.3 Bulk alignment material

Novel materials have been developed [4] that allow for photoalignment of anisotropic materials in the bulk without an alignment layer. Liquid crystal photoinitiators are a key component of formulations that can be processed in such way. This property is typically exploited by flood exposing the material with polarized UV light, with a peak emission wavelength of $\sim 365\text{nm}$. It is theoretically possible to photopattern these materials [5], which has been realized previously using simple amplitude masks with flood exposure UV light. In this paper we report the photopatterning of such materials using visible (406nm) coherent laser light. By using a similar interferometric polarization grating writing method that is described above, an example of a grating with a PB pitch of $\Lambda=10\mu\text{m}$ was produced on a glass substrate without an aligning layer. Fig. 5b illustrate successful photopatterning of a complex structure into the bulk aligning material with the grating structure clearly visible. To confirm that the structure is indeed a continuously rotating director profile, an achromatic $\frac{1}{4}$ wave plate was placed in front of the sample.

3. LC for AR/VR Applications

It has been envisaged that LC materials have the potential to impact on AR/VR devices as part of the light engine, active lenses and potentially in the combiner unit. Many AR designs contain an LCOS panel as the image generator in the light engine. Although existing LC materials satisfy most performance requirements for this technology there is still the need to develop mixtures that

have higher birefringence (Δn), and which are fast switching. It is well known that faster switching LC mixtures can be prepared by reducing rotational viscosity (γ_1), however this becomes increasingly difficult for high Δn liquid crystal mixtures.

As can be seen in Fig. 7, the general trend is for rotational viscosity to increase with increasing Δn . Another trend is that negative $\Delta\epsilon$ LC mixtures generally have higher rotational viscosity than positive $\Delta\epsilon$ mixtures. When positive $\Delta\epsilon$ LC mixtures with $\Delta n > 0.35$ are included, the correlation of increasing birefringence and increasing rotational viscosity continues. However, these particular mixtures are generally not suitable for applications in which visible light is used. Another important factor to consider is that often the clearing point of the mixtures can also significantly increase with birefringence. This is especially apparent with negative $\Delta\epsilon$ LC mixtures.

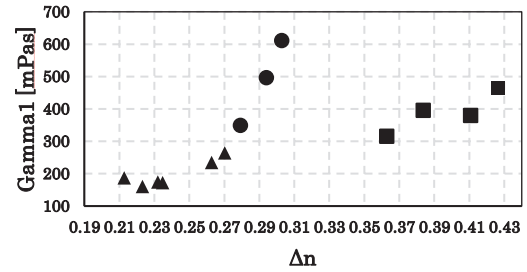


Fig. 7 Change in γ_1 with birefringence for three groups of LC mixtures. [▲] positive $\Delta\epsilon$, [●] negative $\Delta\epsilon$, and [■] positive $\Delta\epsilon$ for IR LC applications

Using high birefringence mixtures in LCOS panels also allows the panel maker to reduce the cell gap for a given retardation value. Thinner cell gaps have a beneficial effect on switching speed. As can be seen in Equations 1 and 2 [6], the response time of the LC has a linear relationship to the γ_1 , $\Delta\epsilon$ and elastic constants. However, it is quadratically proportional to the cell gap. Therefore, increasing the birefringence of the LC mixture allows for a reduction in the cell gap, and a significant improvement in switching time. This becomes even more important in optical designs in which the light engine is required to modulate the phase which typically need retardation of 2π .

$$\tau_{rise} = \frac{\gamma_1 d^2}{K\pi^2 \left[\left(\frac{V}{V_{th}} \right)^2 - 1 \right]} = \frac{\gamma_1}{|\epsilon_0 \Delta\epsilon| E^2 - \frac{\pi^2}{d^2} K} \quad (1)$$

$$\tau_{fall} = \frac{\gamma_1 d^2}{K\pi^2} \quad (2)$$

A well-known challenge with increasing the birefringence of a liquid crystal mixture is to maintain good light stability. The intensity and wavelength that the LC material experiences depends on the application and light source. In the case of LCOS, then certain applications use narrow bandwidth light sources that contain limited amount of harmful UV light. By measuring the change in the voltage holding ratio (VHR) of LC mixture over time, the effect of specific light sources on

light stability of the mixtures can be monitored. An example of how the VHR of a mixture with positive $\Delta\epsilon$ and a Δn of 0.245 changes on exposure to a high dose of 460nm light is shown in Fig. 8. As can be seen, VHR of the mixture slightly decreases over time, but using special additives, the light stability of these mixtures can be significantly improved.

In some headset designs, dynamic lenses are included in the design. Although liquid crystal lenses have been commercialized for various applications including cell phones, they have some well-known limitations [7]. These include a limited aperture size, and relatively slow response time. A thicker cell gap is one solution to creating a larger aperture size, but this can also lead to lenses with slow response time. Several solutions have been proposed in the literature, including using dual frequency liquid crystals (DFLC) so that both T_{on} and T_{off} can be driven by field. DFLC mixtures have been known for many years, however they suffer from several drawbacks including a high crossover frequency which can lead to high energy consumption [8].

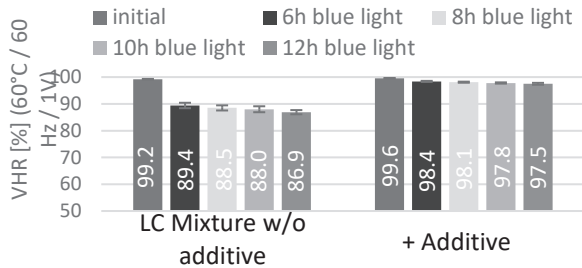


Fig. 8 Effect of light exposure on a LC mixture with a birefringence of ~0.245 with and without additives

From a LC mixture formulation perspective, the challenge with developing DFLC is that a key component is the positive $\Delta\epsilon$ molecule that is both highly polar and has sufficient molecular length that it's electrical response changes with frequency, but that is also sufficiently soluble with the rest of the mixture which are intended to give the negative $\Delta\epsilon$ characteristics. By way of example, new formulations, DFLC-1 and DFLC-2 have been developed which have the properties described in Table 2.

Table 2 Properties of newly developed DFLC mixtures

	MLC-2048	DFLC-1	DFLC-2
T_{ni} [°C]	106.5	115.0	109.5
Dn (589nm 20 °C)	0.2214	0.2246	0.2227
De	3.1	3.0	3.3
e_{para}	10.5	11.9	12.9
e_{perp}	7.4	8.8	9.6
K_{11} [pN]	16.1	17.5	16.9
K_{33} [pN]	22.4	22.3	19.6
Crossover f [kHz]	12.5	7.0	6.0

The key improvement point compared to the well-studied MLC-2048 is the lower crossover frequency whilst maintaining other important parameters. The low temp. stability of this mixture has been measured at over 1000 hours at -20°C. The variation of crossover frequency with

temp. is like that demonstrated by MLC-2048. The frequency response of DFLC-1 is shown in Fig. 9. The permittivity changes from positive to negative at 7kHz.

By way of example, new formulations, DFLC-1 and DFLC-2 have been developed which have the properties described in Table 2. We anticipate that further improvements of important DFLC parameters such as birefringence and crossover frequency whilst maintaining good thermal stability, may be possible.

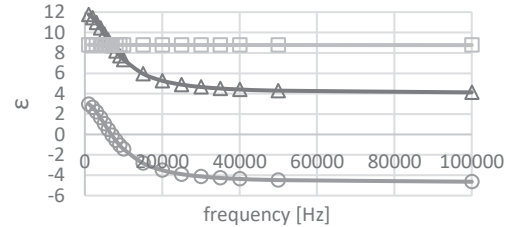


Fig. 9 ϵ parallel [Δ], ϵ perpendicular [○] and $\Delta\epsilon$ [□] as a function of frequency for DFLC-1

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