Liquid Crystal Active Glasses for 3D Cinema

Abhishek K. Srivastava, J. L. de Bougrenet de la Tocnaye, and Laurent Dupont

***Abstract*—Liquid crystals have been extensively studied and are massively used in display technology. Their recent use to provide optical shutters in active glasses for 3D cinema has focused the attention on new specific requirements. Recent improvements in the quality of 3D movies production and projection (e.g., involving triple flash projectors) resulted in the need for high quality glasses with no ghosting, no color banding, large viewing angle and good residual light. We present here the main relevant parameters to assess the quality required today by the studios and we compare the main liquid crystal options which can be used with their respective advantages.**

***Index Terms*—Color measurement, electro-optic effects, liquid crystal devices, stereo vision.**

I. INTRODUCTION

THREE-DIMENSION (3D) technology is all about creating a sense of depth for the viewers. It is not to be confused with images created in 3D (also referred as computer-generated images, or even 3D) but displayed in 2D. Most 3D technologies fall into one of four categories: 1) stereoscopic (requiring to wear special glasses) [1]; 2) auto-stereoscopic [2]; and 3) volumetric and 4) holographic [3], both of which do not need glasses, but require that viewers be in a sweet spot and enormous amounts of processing power. Recently, 3D has made inroads in the consumer market, particularly, in home theatre and cinema due to the adoption of digital projection to replace celluloid 35-mm projectors. A new 3D has come to maturity with significantly better 3D experience, easy and affordable projection systems for cinemas, and more creative 3D content. 3D images require the creation of a left eye and a right eye image with slightly different perspectives. Both images are then projected on the screen and special glasses are used as filters so that only the left eye image goes to the left eye and the right image to the right one. Different filtering technologies are used: light polarization [1], color filters [4], and active goggles [5] (also called shutter goggles due to the use of a liquid crystal cell that opens and closes alternatively at high speed). The current demand for 3D high quality resulted in an increase in image refreshing rate from 96 image/s (double flash) to 144 (triple flash), to restitute 3D motions with the same image and color quality. The triple flash scheme enables a smoother motion but requires an increase of the dark time (Fig. 1). This leap rises to a first technical breakthrough requiring fast liquid crystal technology to prevent image ghosting, color banding and residual light reduction. The second trend concerns goggle design and functions to meet exploitation constraints (e.g., robustness, cost effectiveness, and viewing angles enabling equal vision comfort at any cinema seat). They should be comfortable, have a low weight eyewear ($<$ 1.3 oz), low power consumption. In terms of optical quality, six main features are relevant to meet the current studio requirements: response time, residual light, luminance viewing angle, chromatic response, contrast, and haze.

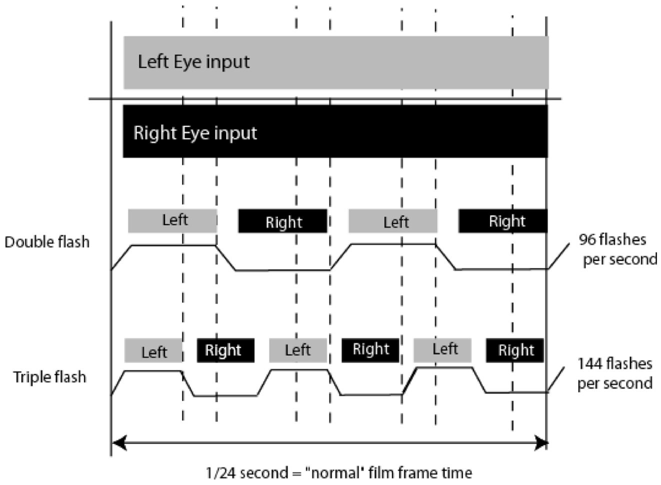

Fig. 1. Timing diagram for both double and triple flash for switching left-high and right-low without consideration of the dark time.

Low performance among these features results in typical visible defects such as ghosting and color banding [6]. For stereoscopic 3D the ghosting is an insufficient filtering between the right and left pictures, resulting in a blurred display due to the shift between the stereo pairs. Color banding is an inaccurate color presentation, due to bit missing to render images in the visible spectrum (i.e., the most significant bits, first displayed) resulting in abrupt changes between shades of the same color. It occurs when glasses are not triggered with the projector or if the shutter switching time is too slow. Ghosting occurs, for active shutters, when the contrast is poor and glasses are either not correctly triggered or have slow switching responses. In this case, a part of the picture for the left eye is shown during the right eye opening. Viewing angle limitation and color dispersion modify the luminance and color balance as a function of the angle (e.g., at the screen edges), therefore modifying the original movies color gamut.

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A. Liquid Crystal Structures for 3D Shutters

Liquid crystals have been extensively studied for manufacturing color flat panel display and laptop devices, involving various smart addressing (e.g., thin-film transistor in active matrix) as well as alignment techniques (in-plane switching [7] or advanced fringe field switching). Most of them own superior performance, color gamut and high luminosity, but require high voltages in a pixel orientated technology not suited to low cost and power consumption. In contrast to the display technology, liquid crystal shutters for 3D cinema should be cost effective, easy to manufacture, and driven by low voltage. The first to be used is the π-cell nematic thanks to a good trade-off between optical quality and low response time (1-3 ms) [8]. We propose here to compare its performance with uniform nematic (thin cell), twisted nematic and smectic C* cells. Before that, we will briefly present the differences between these structures.

1) Uniform Nematic and Thin Nematic: Only the planar configuration is relevant here. The response time depends upon the viscosity, the dielectric anisotropy and the square of the electric field. The major limitation is the intrinsic material elastic relaxation resulting in slow response times (few ms). It is why thin nematic is preferred (1-2 μm instead of 5-6 μm for uniform nematics), knowing that the thickness reduction impacts the switching time, the viewing angle and the chromatic response, provide the appropriate birefringence is chosen to operate as a half wave plate. It is easy to manufacture and reliable.

2) π-Cell Nematic: First proposed by Bos [8], it uses the backflow to speed up the switching time. In the standard configuration, cells have a molecule uniform alignment with a pretilt angle in the opposite direction. After the electric field is switched on and off, the molecules relax back to the original state, causing a flow. The molecules in the mid-layer feel a torque, causing a back-flow, which rotates them to the original state. The angle to tilt back is small, which causes a faster switching speed. The π-cell has an intrinsic good viewing angle due to its self-compensated structure, and switching responses in the range of 1-3 ms depending on the material choice.

3) Twisted Nematic (TN): In contrast to the uniform case, glass plates are generally rubbed in perpendicular orientations, therefore inducing a twist [9], [10]. When no field is applied to unwind the twist, the cell exhibits optical activity for a polarized light (compensated in the reflection). TNs have large modulation ranges with respect to (w.r.t.) the applied voltage, resulting in a better control of the birefringence modulation and a lower dependence to thickness variations, but slow response times (about 10 ms).

4) Ferroelectric SmC:* The electro-optic effect is due to the smectic cone rotation driven by the coupling between the spontaneous polarization P_s and external electric field E. In contrast to nematic, this effect depends upon the field polarization. Furthermore, ferroelectric coupling is generally greater than the dielectric coupling. This point is at the origin of the fast response time, given by

$$\tau = \frac{\gamma_\varphi}{P_s E} \tag{1}$$

with γ_φ the smectic rotational viscosity. Typical switching times of 10–100 μs are obtained. However, if smectics own fast switching, they are more difficult to manufacture over large size due to specific defects formation. A way to overcome such drawbacks is to combine them with polymer networks working as stabilizer, to prevent defect formations and make devices more robust against chocks. Such a material is called polymer-stabilized ferroelectric liquid crystal (PSFLC). These solutions have been extensively studied and are nowadays manufactured easily [11].

II. EXPERIMENTS AND RESULTS

Four different liquid crystals: π-cell, PSFLC, thin nematic and twisted nematic have been used. For PSFLC the Felix 15/100 FLC has been stabilized by adding 13% monomer RN 257. To polymerize the monomer in FLC the FLC cell is exposed through UV light in the nematic phase for 10 min. We have shown [12] that such monomer concentration is enough to cancel the intrinsic defects of pure FLC. The nematic Merck mixture MLC 7030 has been used for the different nematics. Luminance viewing angle measurements have been carried out on the EZlite 120SRC from ELDIM. The lighting condition can be extended up to the viewing cone of $+/-60^\circ$. Luminance, contrast, and color dispersion measurements have been achieved using a homogeneous white light (CCF Lamp). The haze has been measured using a 3 W white LED because, under a homogeneous light source, haze values were too small and far from real projection conditions. Response times have been measured by placing the cell between crossed polarizers and illuminated by a HeNe laser. The optical response was recorded by a Newport dual channel power meter 2832-C and processed by a Tektronix TDS1002 digital oscilloscope.

A. Response Time

Fig. 2 shows the response time of the different liquid crystals structures. The TN is the slowest, as expected, having a response time of 22 ms, due to some fundamental issues like backflow effect [13], [14]. π–cell shows faster response (about 1.25 ms) and thin nematic even faster < 1 ms. These are good values, due to the fact that the chosen materials have a good rotational viscosity (i.e., 48 mPas). The main difference between smectic and nematic remains the switching time and the asymmetrical response between rise and fall times, explained by the nematic relaxation time given by:

$$\tau_0. = \frac{\gamma\, d^2}{K_{11} \cdot \pi^2} \tag{2}$$

where τ_0 is response time γ is rotational viscosity, K_{11} is splay elastic constant and d is the cell thickness [15]. Nematic liquid crystals are driven by electric field acting on their dielectric anisotropy. Hence, they can be turned to the OFF state rapidly because the force is applied by the external electric field. Conversely, the ON-state corresponds to null applied voltage: to switch back to the ON state, therefore, requiring the nematic to relax due to elastic restoring torque. Therefore, the switching times from OFF- to ON-state is limited by this relaxation time (typically a few milliseconds), at the origin of color artifacts (relaxed responses impact the most significant bits of color image encoding of DLP projectors, resulting in color banding). Making thin cells speeds up the response time but not the

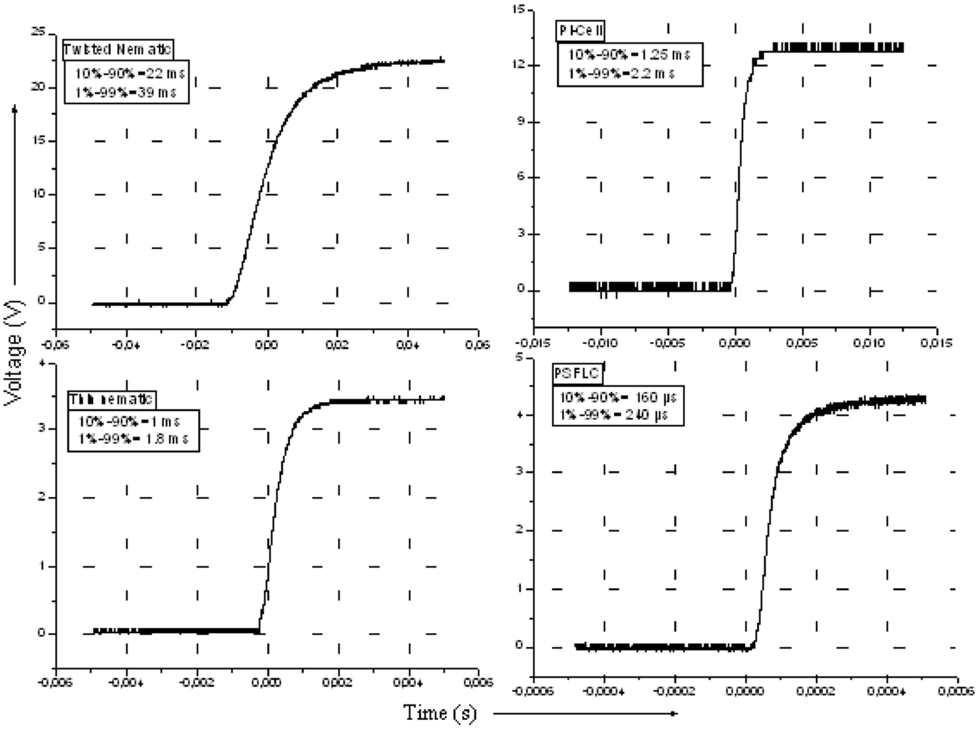


Fig. 2. Switching time for different liquid crystal structures, emphasizing the relaxation time only (the slowest).

relaxation which depends upon γ and K_{11}. The way to improve this value is to modify the elastic force and/or the viscosity taking care of the birefringence reduction or/and operating temperature range.

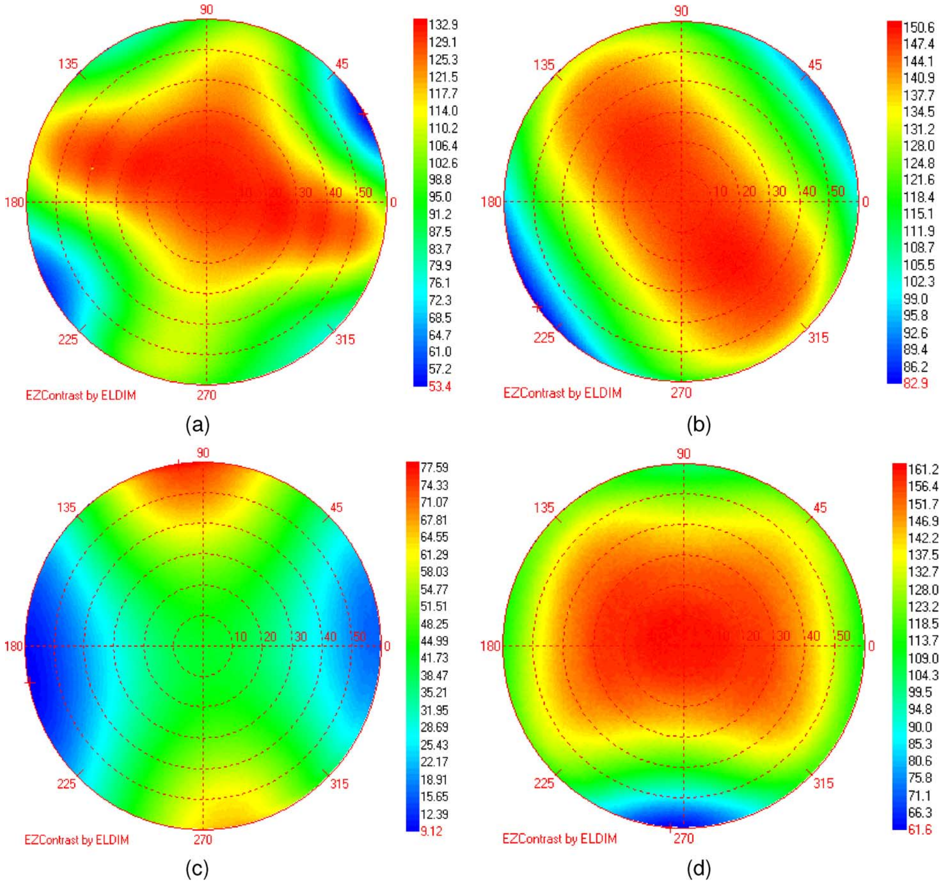
FLC does not exhibit the same switching mechanism, due to the presence of spontaneous polarization perpendicular to the long molecular axis. When a voltage is applied to the electrodes, Ps tends to align parallel to the applied electric field. Hence, depending on the applied voltage sign, the molecules are driven symmetrically to one side of the cone or the other. FLC shutters can be turned to the ON-state (V) and the OFF-state (−V) rapidly, enabling fast switching times (around 100 μs). Consequently, their symmetric switching regimes enable operations with significantly small dark times which can be lowered down to 200 μs (70 μs in [12]). It is the main significant improvement compared to nematics, making PSFLC well suited to triple flash and when dark times are used to trigger the goggle (e.g., with the Texas Instruments DLP® Link™ using a white light emitter from the DLP chip during the blanking time). In that case, it is needed to shut off both eyes during this time. This decrease in dark time results in an increase in the residual light luminance.

B. Luminance Viewing Angle in the ON State

Fig. 3 presents the luminance versus the viewing angle plotted in polar coordinates, in the ON state (the passing state). The figure shows that the luminance is good for all the structures. However, the π–cell exhibits a higher angular dependence in contrast to PSFLC, TN, and thin nematic. It confirms that the light transmitted through the cell is maximum for the TN. The transmittance for uniform nematic, under crossed polarizers, depends upon the cell thickness, wavelength and birefringence as described in [16] and [17]. Use of thin cells improves the response time, the viewing angle and color dispersion but it requires a material optimization for the birefringence and the viscosity to maintain a good transmittance in the OFF state and response time.

C. Residual Light (RL)

It measures the light passing through each glass eye. Few parameters impact this value: the transmission quality, the flash duration, linked to the glass switching time (dark-time length). We measured the luminance with a homogeneous white light source (CCF lamp by ELDIM) with and without the LC cell. The residual light percentage has been computed at a triple flash frequency (72 Hz) without dark time. The CCF lamp luminance is 190 $\mathrm{cd/m^2}$. The residual light, in absence of a dark time, for π-cell, PSFLC, and twisted nematic equals 34.7%, 39.5%, and 42.4%, respectively. The thin nematic was not considered, because its OFF state was not optimized. With dark times, the LC switching response impacts the RL significantly. Fast switching time enables operations with significantly smaller dark times. The π-cell and thin nematic have near about the same response time. Therefore, the RL will be almost the same for both of them while it differs from the PSFLC cell. The TN is not compatible with the triple flash technology because too slow. After few tests in real conditions, we have found that a dark time up to 200 μs is possible without color banding with the PSFLC. This value enables displaying a frame during 6.8 ms instead of 6 ms (for a 6 ms frame, the dark time is 1 ms). Color banding could occur with the nematic technology, under triple flash. It can be understood from Fig. 4, showing the correlation between the flash duration and the time needed to switch from right to left eye frame for different liquid crystal structures. Hence, the equivalent light,



(a) (b)

(c) (d)

Fig. 3. Viewing angle dependence in on state for: (a) π-cell; (b) PSFLC; (c) thin nematic; and (d) TN. The luminance intensity is in $\mathrm{cd/m^2}$.

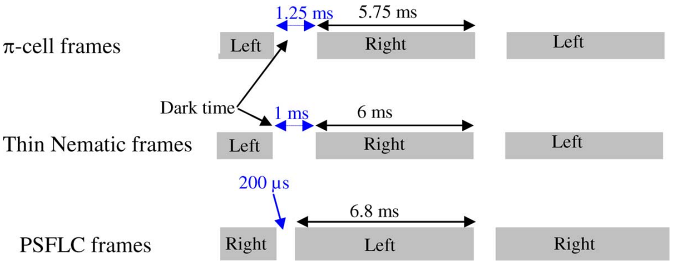


Fig. 4. Frames displaying comparison between the nematic and PSFLC technologies.

passing through goggle, decreases for different LC structure according to their dark time, consequently the residual light also decreases. The flash duration for the π-cell and thin nematic is almost same but for PSFLC (i.e., 6.8 ms) it is 11.76% better than the nematic flash duration (i.e., 6 ms). Thus using triple flash technology the equivalent residual light for nematic and PSFLC becomes 29.74% and 38.37%, respectively, i.e., 29.12% better for PSFLC, than nematics.

D. Contrast Ratio and Blocking State

Good blocking state (OFF state) is a high demand for active glasses in 3D cinema. If the blocking state is not good enough and exhibits angular dependence, ghosting would appear when the viewers rotate their head. To check the quality of the blocking states and its angular dependence for different structures, the luminance has been measured in the OFF state (Fig. 5). π-cell and twisted nematics show a significant angular dependence. In contrast, the OFF state of PSFLC and thin nematic is much better. It is due to the complex geometrical structure in the bulk of π-cell and twisted nematic compared to the thin film structure of PSFLC and thin nematic.

EZYCom (i.e., EZYlite software) enables the measurement of contrast ratio and ISO contrast. The contrast ratio has been taken as the ratio of luminance in the ON and OFF states. Usually nematic liquid crystals have better on-axis contrast than smectics [18]. Nevertheless, a contrast of 1:30 over a large viewing angle is currently sufficient to provide satisfying 3D movies visualization. Fig. 6 shows the viewing angle dependence of the contrast ratio for all the structures. The contrast ratio for π-cell shows high angular dependence and it is around 1:130. Thin nematic and TN exhibit contrast ratio of 1:140 and 1:700 and show less viewing angle dependence over a large viewing cone. For PSFLC the contrast ratio is small i.e., 1:40. This is due to intrinsic FLC geometry defects. The polymer network used to stabilize does not improve this parameter significantly [19].

We notice that the viewing angle dependence in ON and OFF states and the contrast ratio for π-cell and twisted nematic structures is not good due to higher angular dependence which may result in some quality reduction for 3D visualization [6]. The contrast ratio for PSFLC is small but this parameter does not

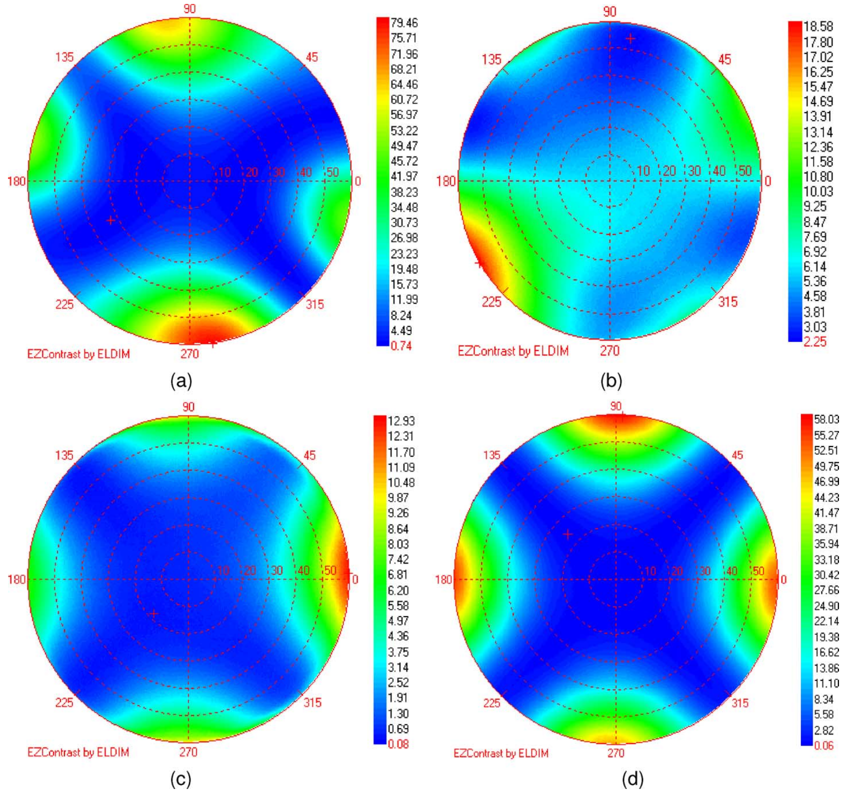


Fig. 5. Viewing angle dependence in OFF state for: (a) $\tilde{\pi}$-cell; (b) PSFLC; (c) thin nematic; and (d) TN. The luminance intensity is in $\mathrm{cd/m^2}$.

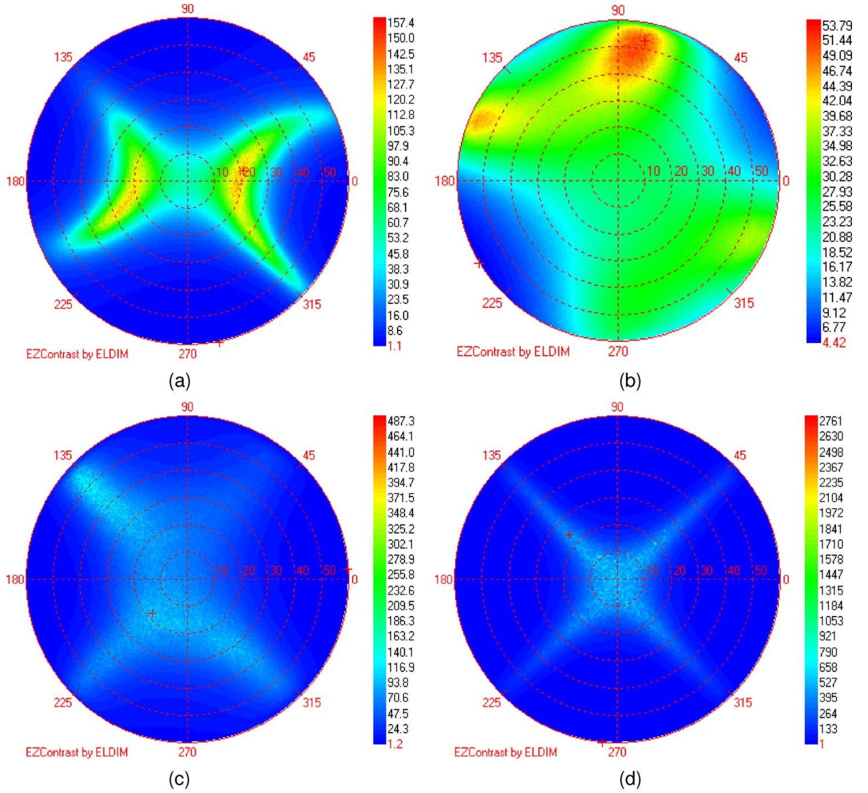


Fig. 6. Angular Contrast ratio for: (a) $\tilde{\pi}$-cell; (b) PSFLC; and (c) thin nematic; and (d) TN.

impact directly the image quality. In contrast its fast response time (160 μs) provides a serious advantage. The thin nematic shows a better contrast, and similar weak angular dependence due to its thin film structure.

E. Angular Chromatic Dispersion

Color dispersion in ON states is the last critical parameter to decide about the quality of the active shutter. Usually color

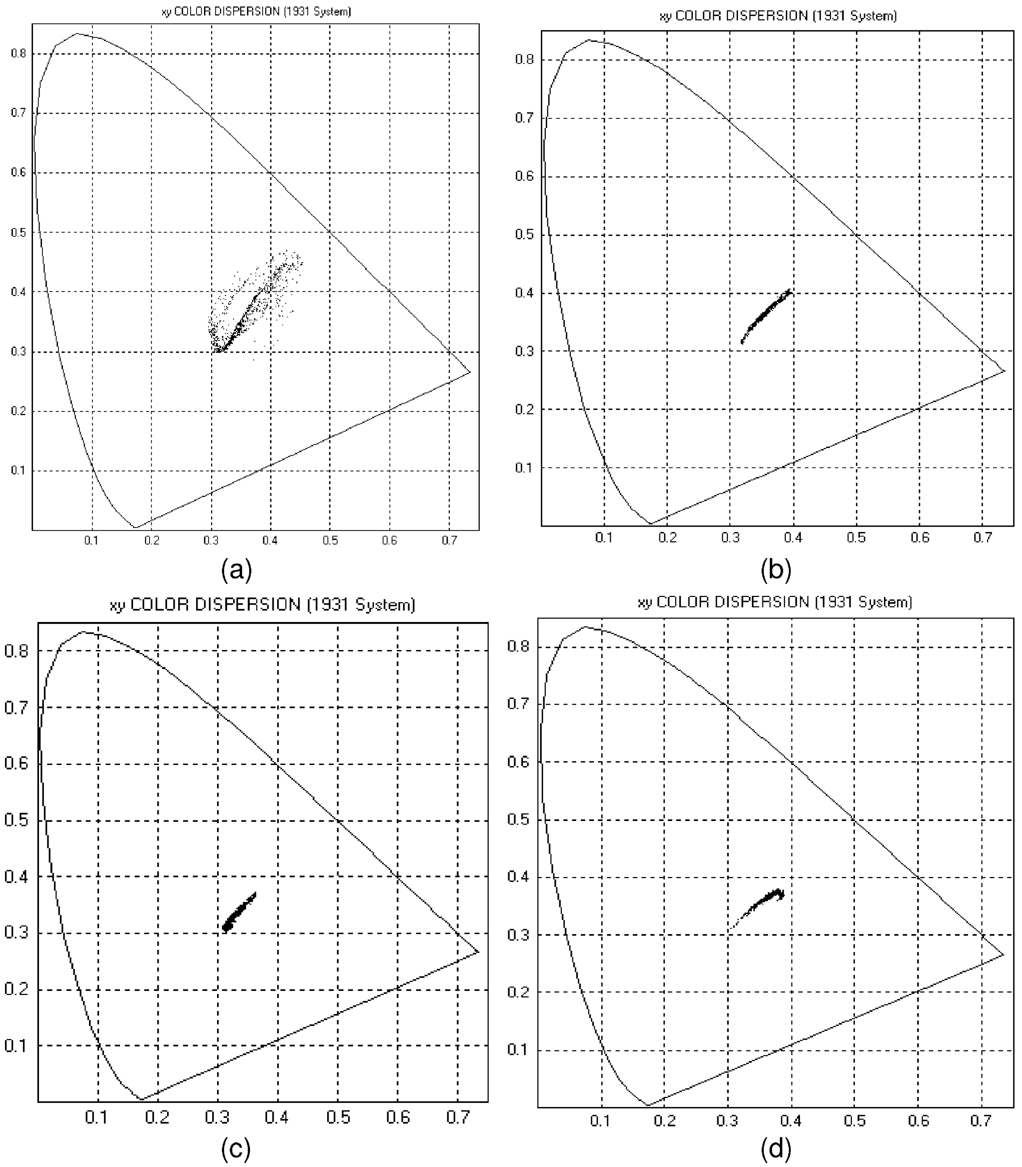


Fig. 7. Angular color dispersion curve in ON state for: (a) π-cell; (b) PSFLC; (c) thin nematic; and (d) TN.

dispersion is observed when the planes of a transparent body in between an observer and a source of light are not parallel, but in the case of active shutters it appears due to the molecular alignment and confinement (e.g., thick helical structures can exhibit Bragg dependence). If color dispersion is large the original movies color will be modified through the goggles. Therefore, it is important that liquid crystal structures show low color dispersion in the ON state. The color dispersion mappings for all the structures, in ON state are shown in Fig. 7 using the CIE 1931 chromaticity diagram [20]. The color dispersion has been measured by the EZlite 120SRC. From Fig. 7 we see that the color dispersion is maximum for the π-cell. The color response for the other structures is good as they show small dispersion for a viewing cone of 60°. This is due to the fact that π-cell has most complicated molecular orientation in the ON state among all the considered structures [13]. For thin nematic the molecular structure is homogeneous, showing low dispersion in the ON state. Another reason for the better color dispersion performance of PSFLC and thin nematic structures is their small cell thickness (1.5 μm).

F. Haze Measurement and OFF State Scattering

Another important feature is the degree of cloudiness. Haze measures the cloudiness, caused by scattering of light. Light may be scattered by particles suspended in the medium (pigment particles, dust) or by imperfect surfaces or fine texture (e.g., polymer networks). Haze is an important attribute used to assess the transmission quality of an object. Transmission haze is defined as the forward scattering of light from the surface of a nearly clear specimen viewed in transmission and expressed as follows:

$$\%\text{Haze} = \left(\frac{T_{\text{diffuse}}}{T_{\text{total}}}\right) \times 100. \tag{3}$$

In practice, this feature measures the cell scattering. Scattering is particularly annoying in the OFF state. Measuring the

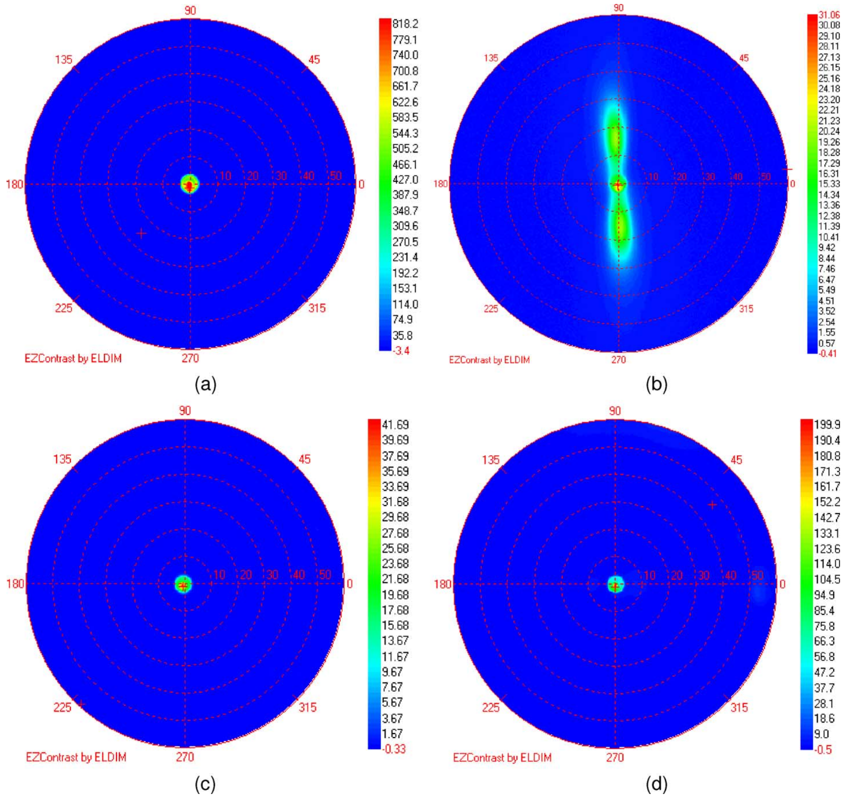


Fig. 8. Luminance (cd/m^2) viewing angle measurement for scattering with white light LED in OFF state. (a) π-cell. (b) PS FLC. (c) Thin nematic. (d) TN.

Haze with the white homogeneous light source provides an average value, for all the LC structures $< 1\%$, considered as satisfying. However, a more advanced analysis shows that the PSFLC exhibits, under certain illumination conditions (bright dots on black screen) a scattering direction. Therefore, to assess this effect we substitute the uniform white source by a white LED point source (from Roithner Laser Technik, Austria). Measurements in the ON state are satisfying and no particular scattering direction is observed. In the OFF state the luminance viewing angle is shown Fig. 8. A scattering appears for PSFLC, even if its level is low. It exhibits two sided scattering lobes in a direction perpendicular to the PSFLC cell rubbing direction.

If we measure the relative haze in this direction we notice that intensity of the lobes is about 70% of the overall scattered intensity and cannot be ignored. Scattering peaks have already been reported with pure FLC materials [21]. The angular location of these diffraction peaks depends upon the cell thickness, since the period of stripe defects in FLCs is strongly correlated to the geometric characteristics of the cell. The stripe defect texture is similar to a birefringent grating with pattern parallel to the rubbing direction. In the case of PSFLC, we observed strong broadened scattering peaks due to mechanical stresses induced by the polymer network on the smectic layers. These constraints induce a dispersion of smectic layer undulation period and therefore a peak broadening. The chromatic dispersion of the scattering due to the white source plays a restricted role in the broadening since the extended scattering lobes are observed in the PSFLC even with a monochromatic source. However, in practice, for cinema, this phenomenon is not much significant and lies under the visualization limit of the eyes. But for isolated brighter objects in dark background a clear scattering in a perpendicular direction to the screen appears that could impact the 3D visualization quality. This effect can be mitigated, by removing the lobes outside a given acceptance angle (let say $+/-30^\circ$) by acting, for instance, on the cell thickness. Another possibility is to reduce the polymer concentration coupled with a strong alignment layer in a more defect free FLC configuration. These parameters can be adjusted according to available mixture choices.

G. *Noisy Thin Cells*

The advantage of using thin cells to improve the chromatic and viewing angle characteristics could be balanced by some undesirable effects. The counterpart of thin cells is the applied electric field, generally larger than for conventional uniform nematic, TN, or π-cell (even if requiring the same voltage value). A consequence, when using thin glass substrates (to save weight) is the possible resulting noise. When a voltage is applied to the cells, for instance, at 72 Hz (i.e., triple flash rate) an audible noise could appear due to glass plate vibrations. The polarization and mechanical strain fluctuation causes a continuous noise spectrum. When the applied voltage reaches to its maximum value, the plates tend to attract each other. This attraction force $F$is given by

$$F = -\frac{V^2 \varepsilon_o \varepsilon_r S}{2d^2} \tag{4}$$

with V the applied voltage, S the cell surface, ε_o and ε_r the permittivity of free and dielectric medium and d the cell thickness. During polarization transitions when the applied voltage passes

TABLE I
COMPARATIVE ANALYSIS OF LC STRUCTURES ON THE UTILITY GROUND OF 3D CINEMA

Structure	**Luminance Viewing Angle**		**Contrast**	**Color Dispersion**	**Haze OFF State**	**Noise**	**Residual light**	**Response Time**
	ON State	**OFF State**						
π- Cell	-	-	+	-	+	+	+	+
PSFLC	++	+	-	+	-	--	++	+ +
Thin Nematic	+	++	+	++	+	-	+	+
Twisted Nematic	++	-	++	+	+	+	*	--

* Not compatible with the triple flash technology.

through zero, the charge densities become null and plates get relaxed. This vibration of glass plates could result in the annoying noise. This becomes very important for thin structures having large surface area, as for the PSFLC and thin nematic, because the force of attraction increases significantly when d decreases. This noise is more critical for PSFLC because of the higher dielectric constant. Due to the high dielectric constant the charge density increases and the attracting force, between the plates, is higher and consequently the noise as well. This effect can be mitigated by optimizing the glass substrate thickness and size and by modifying the electric driving scheme of the cell [22].

III. DISCUSSION

On the above analysis, we derived Table I comparing the main liquid crystals according to the relevant parameters measuring the appropriateness of active glasses for cinema uses.

As said before, the comparison has been made on the basis of basic liquid crystal structures those are easy to manufacture and have low threshold voltage. This comparison suggests that thin nematic are the best compromise for active glasses. According to current trends in 3D cinema, the material should be optimized for birefringence, viscosity etc. also the noise issue must be addressed in case of using thin glass substrates or plastic foils. Thin nematic structures provide best transmission quality in term of viewing angle and chromatic dependence, with a good switching response for nematics (1 ms in the present case). However, this value could be insufficient when operating at triple flash frequency and some undesirable effects such as color banding could appear for some movies. According to this feature, smectic materials (e.g., FLC or PSFLC) offer obviously the best resource in terms of switching response. Even though, this advantage is not clearly decisive for the 3D cinema. This feature could become critical when blanking times are used for other purposes such as Texas Instruments DLP® Link™ to synchronize glasses, for home video applications. In that case, it will be necessary to shut off the glasses during this time. This constraint combined with a dark time reduction imposes faster switching time and symmetric responses. PSFLCs are capable to have switching time smaller than 100 μs thus these are particularly appropriate for such technical trends. In contrast, they require a more complex process to avoid some structural defects such as the scattering and noise. Finally, two contestants stand up from our analysis: thin nematic and FLC or PSFLC, confirming that thin materials are appropriate for such an application. Noise, which can result, can be bypassed by using either thick glass plates or appropriate electrical driving schemes, or both. Their compatibility with plastic foils would be probably another challenging issue in the future for the technology world.

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