ADVANCEMENTS IN LUMINANCE VIEW ANGLE DISTRIBUTIONS IN LIQUID CRYSTAL DISPLAYS

by

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I dedicate this Master's Report to my family and friends – especially to my husband, Alex – who have supported me through my pursuit in the Optical Sciences. I am so grateful for your loving encouragement in these four years.

LAND ACKNOWLEDGEMENT

We respectfully acknowledge the University of Arizona is on the land and territories of Indigenous peoples. Today, Arizona is home to 22 federally recognized tribes, with Tucson being home to the O'odham and the Yaqui. Committed to diversity and inclusion, the University strives to build sustainable relationships with sovereign Native Nations and Indigenous communities through education offerings, partnerships, and community service.

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Abstract

Liquid crystals are the integral component of liquid crystal displays (LCDs) used in many consumer electronics applications that require high-performing optical characteristics. In form factors like televisions, near-eye displays, and automotive displays, the wide-viewing angle quality is a critical factor that requires quantitative design and polarization engineering. Since the first commercialized Twisted Nematic (TN) LCD in 1973, there were many efforts to solve for a wide-viewing angle display. As a result, the developments in LC materials, architectures, and polarization compensation films increased the off-axis contrast by an order of magnitude. The impact of these components has further secured LCD as a cost-effective, high-performing option for mass production displays.

Introduction

Liquid crystal displays (LCDs) are a standard option in today's display industry due to high-performance and yield across many of applications. Yet the road to this point had many challenges. The early TN-LCD modes were revolutionary in 1970 because they were mass produced and power efficient for small displays used in pocket calculators and wristwatches. However, as display applications grew to require larger sizes and accommodate more products, so did the number of optical challenges to address; the uniformity, response time, and viewing angle were all concerns. In particular, the viewing angle quality was a critical factor that required intensive study of liquid crystal materials and the surrounding architecture.

Liquid crystal fundamentals and display optics are examined in the report's first section. They are the building blocks of the conventional LC mode that is named as the twisted-nematic (TN) LCD. In general, liquid crystals are the critical factor in LCDs that modulate the light output in a liquid crystal cell. When a voltage is applied to a cell that has a specified thickness and birefringent LC material, the retardance can be tuned and therefore manipulate the polarization state to act as a switch between crossed polarizers. In a modern display configuration, the LC device incorporates this modulator between two glass plates coated with transparent electrodes that can address a 2D matrix of pixels. Finally, the plates are placed between polarizers where the fast axes are oriented to induce polarization control in the device. Further details describe the specific working mechanism of the TN LCD.

Figure 1: Example renderings of brightness and color performance at different viewing angles for [left] Twisted Nematic (TN) and [right] In-Plane Switching (IPS) display [1].

The second section of the report describes the challenges and advancements in the development journey to optimize the LCD viewing angle brightness across angle and spectrum. The limitations with conventional twisted-nematic (TN) LCD view angle are discussed as well as the optimizations made in liquid crystal materials and architectures like in homogenous alignment, vertical alignment nematic (VAN), and in-plane switching (IPS). Specialized optical films are also introduced as solutions to poor viewing angle including prism, uniaxial, and biaxial polarization films. Overall, these advances have further secured LCD as an effective choice for wide field of view (FOV) display.

Section I: LCD Displays

Role of Liquid Crystal in the Display Device

Liquid crystals (LC) are utilized for their unique optical properties. For display technology, the LC anisotropy and birefringence are among the most important factors to consider in the design and function of the device.

Liquid crystal describes the state of matter for a specific molecule in a mesomorphic phase between a liquid and solid state [2]. The molecules are neither completely disordered, nor in a rigid crystalline orientation. Rather, the liquid crystals can freely rotate the orientation locally, while maintaining a crystal-like order globally. A nematic state is the most common LC used in display industry. The term nematic, originating from the Greek word, *nematos* (meaning thread-like), is one such phase of matter before the clearing point when the LC materials become isotropic and disordered [2]. LC molecules naturally settle to align in a low-energy state by ordering the same way as its neighbors.

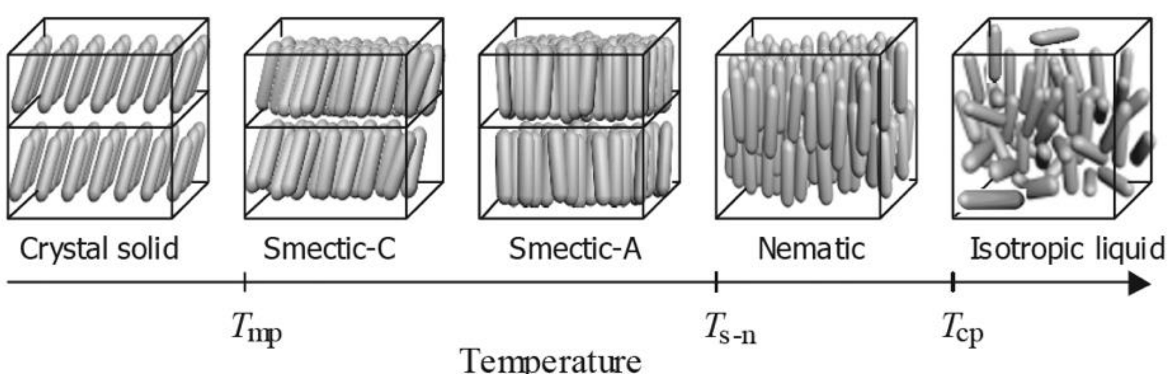

Figure 2: Schematics showing the varying phases of matter for LC as a function of temperature. The three specific temperature points, T_{mp}, $T_{s\text{-}n}$, and T_{cp} are the temperatures for the melting point, smectic-to-nematic, and clearing point, respectively. [2]

LC molecules are anisotropic with a high aspect ratio geometry. It reinforces a naturally occurring dipole moment, where one end of the molecule has an excess of electrons than the center, which induces a charge [3]. An external electrical field causes a torque and rotates the molecules to varying directions; positive dielectric anisotropic molecules would rotate parallel to the applied electric field, whereas negative dielectric molecules would rotate perpendicular.

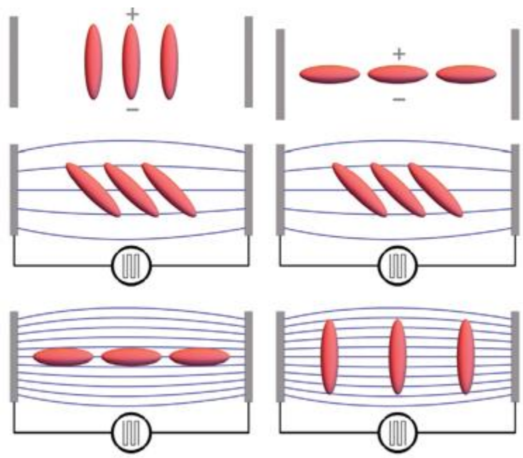

Figure 3: LC molecules are shown before, during, and after a varying effect of the electric field. [Top] The top row shows the 0V state when the LC is relaxed. The positive and negative notation indicate the charge. [Middle and Bottom] In the middle and bottom rows, an increasing electric field lines (in blue) will rotate the LC to a perpendicular orientation from the initial state. The first column demonstrates the positive, or p-type LC (with $\varepsilon_{parallel} > \varepsilon_{perpendicular}$), while the second column demonstrates the negative, or n-type LC (with $\varepsilon_{parallel} < \varepsilon_{perpendicular}$), where ε is the dielectric susceptibility. [2,3]

This anisotropic shape also influences a birefringence since the refractive index is different along the axes of the molecule. In many cases, the largest refractive index is at the director orientation, while the smaller index is perpendicular. Effectively, this provides the birefringence property, $\Delta n = n_e - n_o$ [3]. The birefringent nature of the LC coupled with the ability to rotate its orientation in space allows for electrically controllable birefringence. This effectively opens a large design space for LC modulators of phase, intensity, or a combination of the two. This report is limited to intensity modulators since the human eye can see the effect of intensity in displays, but not phase.

LCD Layout and Polarization Display Optics

The LCD is made of layers that propagate light from an external uniform backlight unit (BLU) through a liquid crystal cell housing. The LCD contains a layer of LC that modulates light through the stack like a shutter by manipulating the liquid crystal molecules with a voltage signal.

The cell is made of two glass plates that sandwich the liquid crystal layer; the plates offer the mechanical support to maintain a uniform cell thickness (or cell gap) and have minimal birefringence to maintain the polarized light state [3]. The layer of glass contacting the LC are coated with at least two additional layers. One is an electrical layer; modern displays source this from indium tin oxide, or abbreviated as ITO. The second is the LC alignment layer that is commonly made from polyimide (abbreviated as PI), which is used to establish the initial orientation of the LC molecules making contact to the glass. [3]

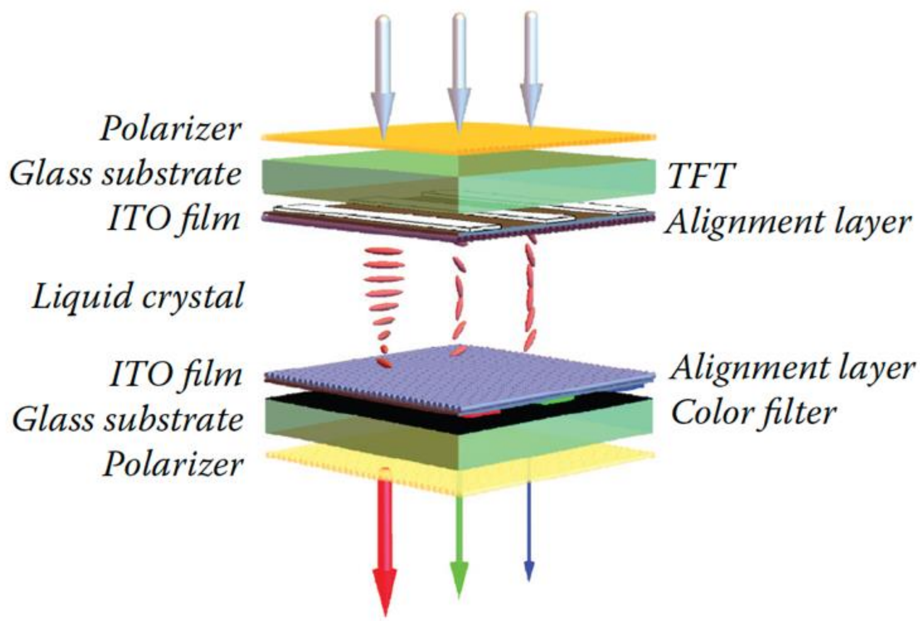

Figure 4: Schematic of the LCD stack in cross-section. In this case, white light is incident from the top and outputs as red, green, and blue. The liquid crystal is enclosed in a cell that is sandwiched by polarizers, glass substrates, the thin film transistor (TFT) and indium tin oxide (ITO) layers for electrical driving, and the alignment layers for LC direction. There are additional color filters patterned on the exiting glass substrate side to transmit the required wavelength through the system. [3]

In a conventional transmissive, color LCD display, an external BLU design is used. There are many architectures for a BLU including direct-lit LEDs or a light pipe on the edge of a panel. Diffuser sheets are used to form a Lambertian profile to shape the light output through the panel. To achieve a typical 300-500 cd/m^2 center luminance, a consumer electronic display needs a BLU on the order of 10,000 cd/m^2 to accommodate the high transmission losses in the stack of layers [4]. Figure 5 explains the impact of each layer on the total transmission, resulting in overall transmissions of <10%. The polarizers, TFT aperture, and color filters all reduce the overall on-axis transmission. One can imagine how the off-axis light output is further impacted at higher angles because of the Lambertian BLU and alignment tolerances of the layer stacks [4].

The orientations of the top and bottom polarizers are a key contributor to the overall LCD light modulation system. It is common to use linear polarizers. In the cross-polarizer case, at least 50% of the transmission loss is from the bottom polarizer. The polarizers are positioned at the outer layers of the LC cell and thin film transistor (TFT) electronics layers. The transmitted light from the BLU is emitted through the bottom polarizer and passes linearly polarized into the cell. Based on the twist of the LC layer and induced retardance of the birefringent material, light will either be absorbed by the output polarizer or pass through the system. Effectively, the intensity modulation function depends on the alignment of the light polarization state to the top polarizer orientation. [3]

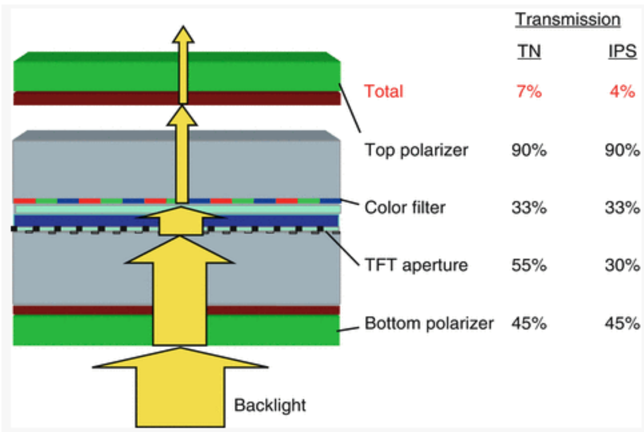

Figure 5: Transmission through the LCD stack has significant losses due to polarizers and other optical layers. With either twisted nematic (TN) or in-plane switching (IPS) liquid crystal, the total transmission out of the display can be less than 10%. [4]

During LCD design, it is important to track the polarization state of the light through each layer to make sure the intended brightness and contrast are achieved. All layers play a part in the system since they can affect the polarization state. For example, some sheet polarizers are coated with a protection of triacetate cellulose (TAC) film, which can induce a small retardance and optically change the polarization state off axis [5].

The transmittance is also controlled by the LCD electro-optical properties. The display emits light at different locations on the device by individually controlling the modulation on a 2D grid of LC cells whose structure defines the pixel resolution. In modern displays, a common electrical architecture is the active matrix (AM) LCD. It contains an electrical grid of switches managed by a thin film transistor (TFT) layer. This layer is made of a transparent, conductive material with an assigned electrical source, gate, and drain for each pixel [2]. In the off state, when there is no voltage applied, the LC cell is at the lowest energy state. Once the TFT sends the signal to the column and row address of the pixel to turn on, a voltage is applied which induces a strong electric field; the liquid crystal at that location rotates to align to the electric field and therefore transmits the signal through the stack [2]. The LC along the glass walls of the cell, however, will not be moved since they are fixed in place due to the alignment layer and the LC anchoring strength [3]. To produce gray values between the dark and white state, an intermediate voltage is assigned. In summary, the LCD as an opto-electrical device can display detailed information by varying the voltage across each pixel over a certain frame rate.

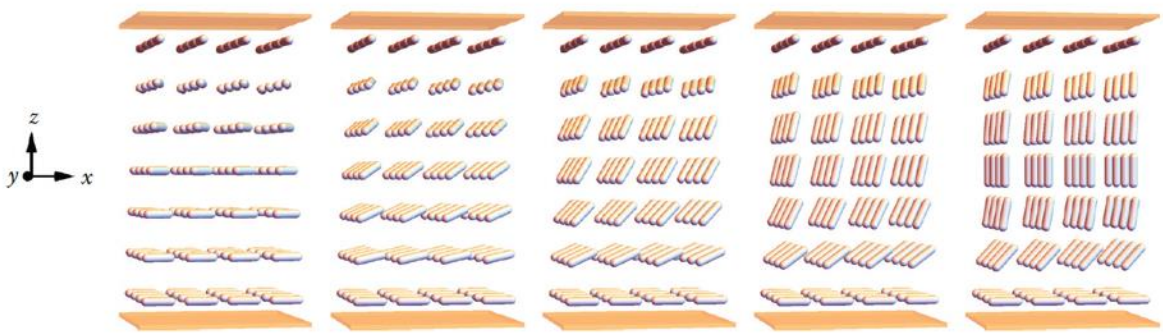

Figure 6: Schematic of the LC directors in a 90 degree TN-LC cell. [Left] No voltage is applied. As voltage slowly increases toward the right figure, the molecules will rotate. The LC at the alignment layers will not rotate. [3]

Twisted Nematic (TN) LCD

One of the earliest conventional architectures of the LC cell in display is a twisted nematic (TN) format. It was formulated in 1970 by W. Helfrich and Martin Schadt at Hoffmann-La Roche, a pharmaceutical company in Switzerland, and in parallel, J. L. Fergason [2]. Shortly after, the TN-LCD was installed into a pocket-calculator manufactured by Sharp. In 1973, over 10 million units were produced, making the calculator the first commercially successful LCD product [2]. The revolutionary design was thinner, a smaller form factor, and more energy efficient; it reduced the power consumption by 4 orders of magnitude compared to the traditional vacuum-tube calculator displays of that time [2]. Soon to follow were TN-LC wrist watches; the “06LC” model Seiko was the first of this kind [2]. The TN-LCD was further incorporated into other technologies, too, like notebook PC displays, monitors, and early cell phones – in sum, LCD makes up a multi-billion-dollar industry [2,3].

Figure 7: [Left] A picture of Sharp's pocket calculator from 1973 which was the first commercial LCD product. [Right] The 06LC model wristwatch produced by Seiko. [2]

The twisted nematic is named after the operational mode in the LC cell, where the LC has a 90 degree twist from the bottom glass to top glass. The grooved alignment layers are sandwiched perpendicular to each other, so the LC will naturally align in a 90 degree twist. In polarization quantities, there is approximately 180 degrees of retardance. When the TN cell is placed between crossed linear polarizers, the light is fully transmitted in the relaxed state; no external voltage is needed to propagate light. However, to block light transmission for a dark state, a voltage is applied so that the LC will untwist and be vertically aligned. The resulting retardance when the director is aligned to the propagation path has zero birefringence and is therefore zero degrees, so this produces a dark state between crossed polarizers [3].

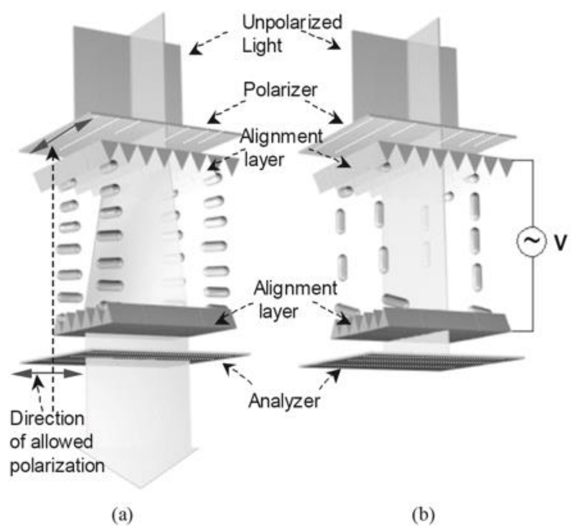

Figure 8: A figure of a TN-LCD in two electrical states. Unpolarized light is incident to the system from the top of the figure. [a] Without applied voltage, the LC is at a 90 degree twist and light is transmitted through the analyzer. [b] When voltage is applied, the LC twists 90 degrees and the light is blocked by the analyzer. [2]

The TN-LCD's optical path length is defined by the birefringence (Δn) and cell thickness (d), and can be related to the total twist angle (ϕ) and wavelength (λ):

$$\Delta n \cdot d \gg \frac{\phi\lambda}{\pi} \quad [2]$$

The LC mode type is a display characteristic that is identified by the polarizer design. In general, the top and bottom polarizer are 90 degrees orthogonal to each other to block the continuous BLU light source and minimize power. However, the orientation of the bottom polarizer to the LC cell director is a design choice. The *e-mode* is the case when the bottom polarizer is aligned parallel to the LC cell director and likewise, the top polarizer is aligned to the LC transmission axis. The *o-mode* is a case where the bottom polarizer and LC director are orthogonal, and therefore the top polarizer is also orthogonal to the twisted LC. At the relaxed state with no applied electric field, the polarization state is determined by the top polarizer, so *e-mode* would transmit light through the analyzer, but *o-mode* would block. Applying a voltage would twist the LC to the orthogonal polarization state to block and transmit, respectively. More rigorous study of the polarization state requires Jones calculus to examine the effects of wavelength and cell design parameters. [3,6]

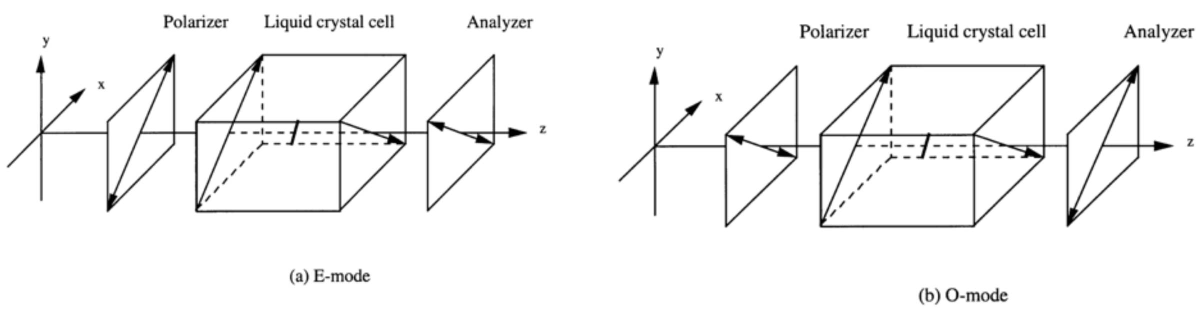

Figure 9: [a] E-mode type of LCD has the first polarizer aligned to the LC direction. [b] O-mode type of LCD has the first polarizer perpendicular to the LC direction. [6]

As the applications for LCD grew, the known deficiencies of TN-LCD's also became more of a concern. Though it had reasonable contrast and power consumption, the view angle was an issue in the first-generation computer notebooks. As a result, there was a strong push for more investments in LC materials, faster response times strategies, and other developments in the industry. The addition of supplemental optical films also showed promising corrections. More details will be discussed in Section 2 about how solutions were driven out of the necessity to improve optical performance.

Section II: Challenges and Advancements in LCD Viewing Angle

Challenge With TN LCD View Angle

After the success of the TN-LCD, displays have continued to penetrate many modern industries as efficient technologies that quickly present information in a variety of contexts. Beyond notebook computers and tablets, the display technology has unlocked solutions for large displays like wide screen televisions, stadium-sized screens, and mid-sized displays for medical and transportation. In automotive displays, designers must specify an acceptable viewing experience that's bright and realistic in color for both the car driver and passenger. Likewise, aerospace displays must achieve acceptable performance for both pilot and copilot. In near-eye displays for AR and VR applications, a virtual image is projected in front of the human eye at a typical 60 degrees FOV. In all cases, displays are being viewed at multiple off-axis angles and therefore the performance of brightness and color must be invariant with view angle.

TN-LCD struggles with wide-angle performance and exhibits severe brightness and color degradation across the horizontal and vertical viewing directions. Two root causes are: (1) retardance change due to a different effective birefringence in the LC cell versus viewing angle and (2) the imperfect extinction between crossed polarizers over versus viewing angle [2,3,5]. As a result, the viewing cone is narrow, asymmetric, and suffers from a leaky dark state [5]. For the first applications of LCDs like calculators and wristwatches, the off-axis performance was not necessary since these products are viewed on-axis. However, this issue started to emerge in the first generation of notebook displays where the gray levels and colors would vary or invert off-axis [2].

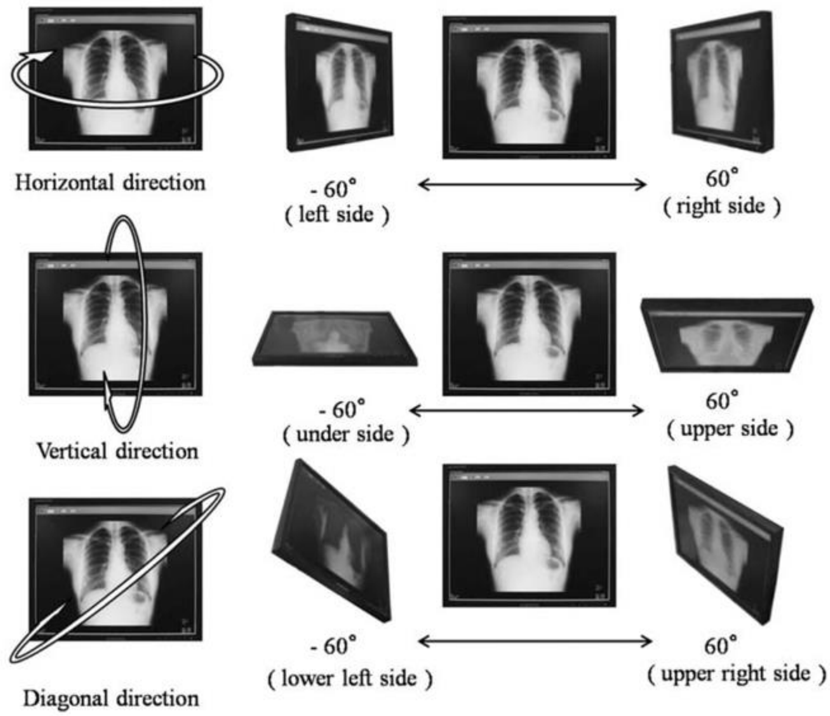

Figure 10: Example renderings of an LCD monitor for a medical application. The brightness across different view angle inspections changes with respect to different polar and azimuth directions [7].

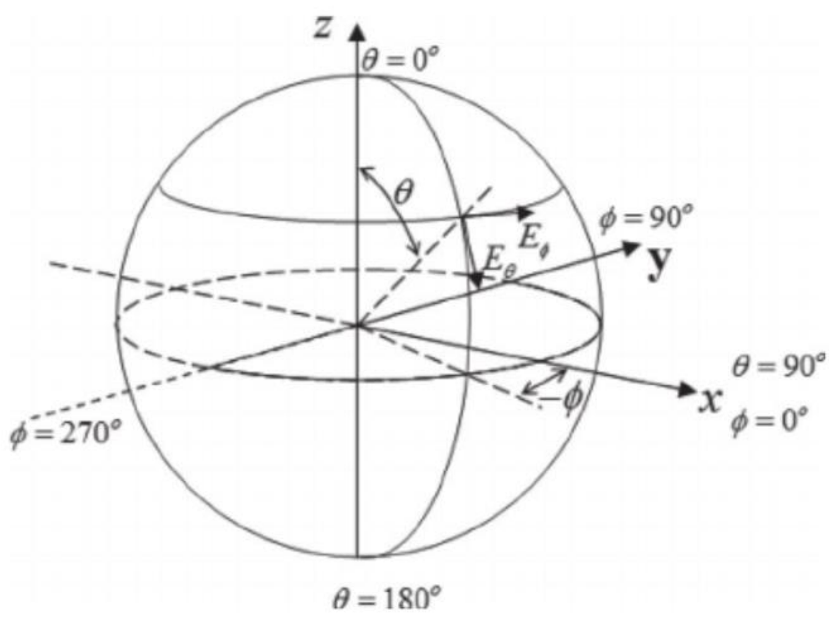

Figure 11: The Type C spherical coordinate system utilized in this report [8].

Retardance Change Over Angle Due to Birefringence

The crux of the issue is shown in Figure 12, which sketches the light path observed at oblique angles. In the TN-LCD, the birefringent LC molecules are twisted by 90 degrees in the LC cell at zero voltage. In Figure 12a, the LC molecule at the middle of the cell is oriented vertically, and all five human eye viewing points do not see any change in birefringence with respect to each other. But as shown in Figure 12b, after an applied voltage, the light path from the display to eye at an off-axis oblique angle passes through a different effective birefringence due to the horizontal orientation of the LC molecule [2]. Overall, there is a variation of the retardance in the system over angle. The light path through the LC to the eye varies by angle and therefore changes the resulting polarization state; this polarization state variation will vary the output transmission out of the top analyzer, so the brightness changes over angle.

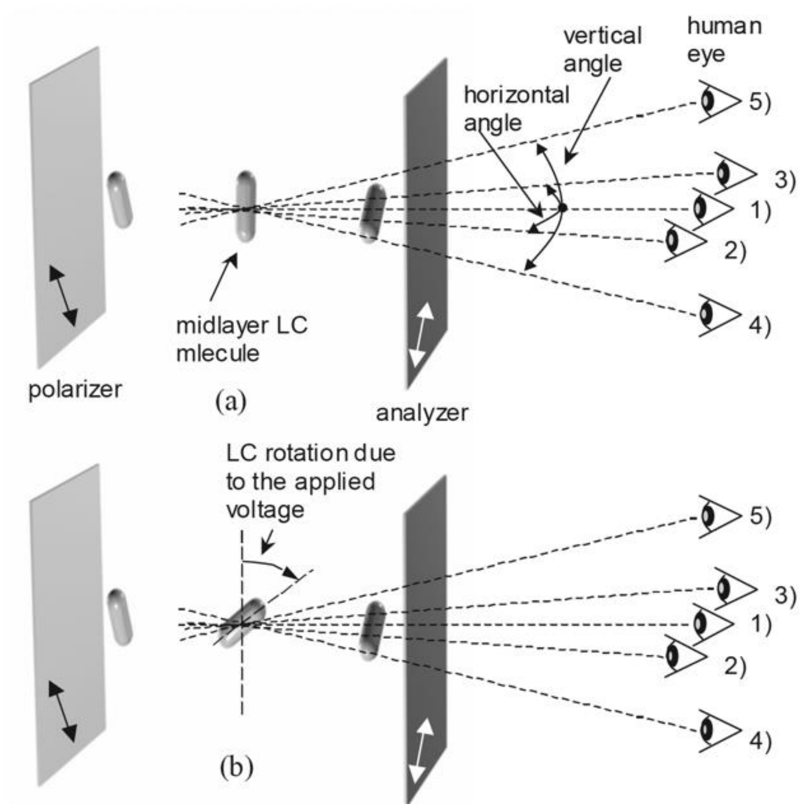

Figure 12: A TN-LCD is shown with five different viewing perspectives, where 1 is on-axis, 2-3 are horizontal azimuth, and 4-5 are vertical azimuth. In [a], there is no applied voltage, so the midlayer LC molecule is vertically oriented and therefore does not cause significant changes in effective birefringence for any light path. In [b], there is an applied voltage, so the LC has rotated and therefore the viewing positions #4,5 have a different effective birefringence than #1,2,3. [2]

The retardance as a function of angle can be visualized with polarization ray tracing software. One specific LC cell (ZLI-1646) was modeled at a wavelength of 589nm [3]. The left plot in Figure 13 explains the map of angle of incidence (AOI) into the LC cell. In the center, the AOI is 0 radians, representing the on-axis light path. However, the AOI increases as a function of radius and is rotationally symmetric; at the edge of the field, the scale indicates the AOI is approximately 0.0755 radians, or 4.33 degrees. The corresponding retardance map at those AOI is shown for the off-state condition like in Figure 12b. At the on-axis location, there is zero retardance. At higher angles, there is a varying increase in retardance as well as some ellipticity impact. The scale indicates a maximum retardance of 1.4598 radians. The ideal map would maintain the same retardance over angle, but the TN-LC mode shows variation. This becomes an issue for the dark state because the initial linear polarization will become elliptically polarized after passing though the cell off axis, and therefore cannot be completely absorbed by the linear analyzer – causing light leakage.

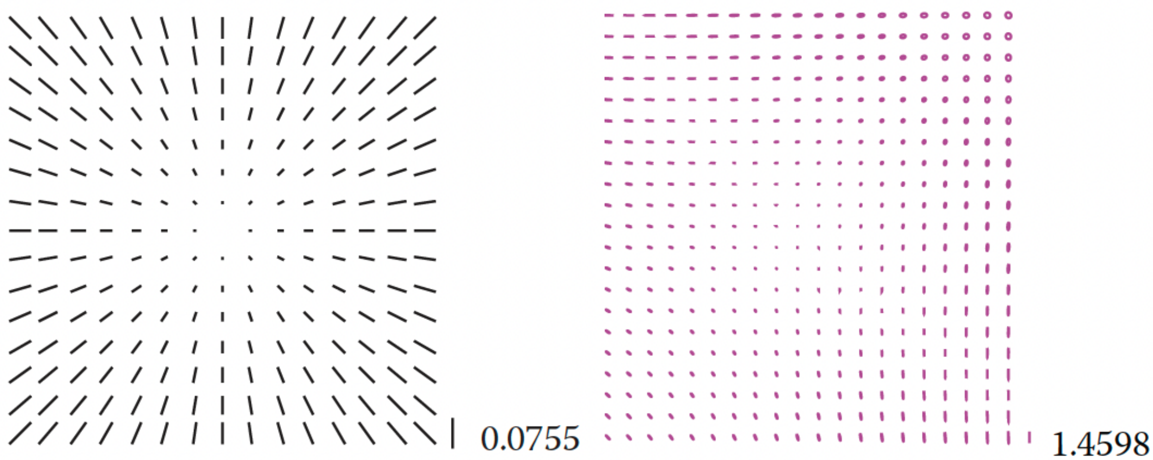

Figure 13: [Left] Angle of incidence (AOI) map for the TN-LC cell (units in radians) at λ=589nm [2]. [Right] Retardance map for TN-LC cell for 5.03V field (units in radians) at λ=589nm [3].

Angular Effect on Crossed Polarizers

The second impact is the effect of crossed polarizers over angle. There is lower contrast in TN-LCD because of the viewing condition at the oblique angles, defined as the angles, defined as the angles not aligned to the transmission axes of the two polarizers. Figures 14 and 15 exhibit this phenomenon with two crossed polarizers. The 0 degree polarizer (shown in pink) and 90 degrees polarizer (shown in green) are stacked together. At the left-most figure, the transmission axes perfectly cancel, so there is no light transmission. If the angle of incidence increases along the 0 degrees azimuth, the transmission axes are still perpendicular and the light is extinguished. [3]

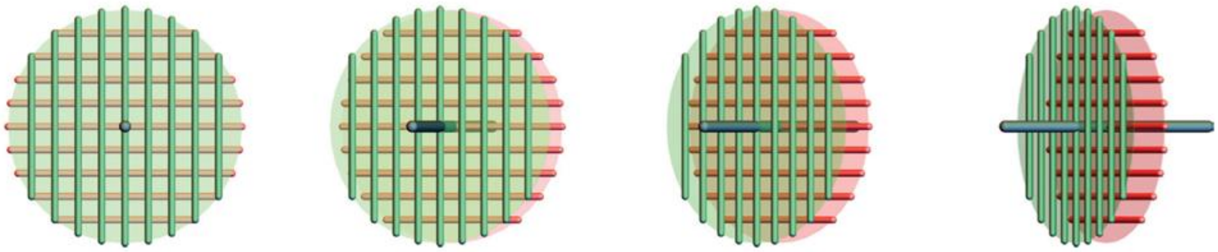

Figure 14: Two polarizers are crossed at 90 degrees with respect to each other. The polarizer in green has transmission axis at 90 degrees, while the polarizer in pink has transmission axis at 0 degrees. [Left to right] As the angle of incidence increases every 15 degrees, the transmission axes are still perpendicular and fully extinguish the incident light. [3]

Another scenario is shown below to demonstrate the light leakage effect. At the left-most figure, there are the same crossed polarizers. From left to right, the angle of incidence increases along the 45 degree azimuth. At these oblique angles, the gridlines are no longer perpendicular and therefore indicate a light leakage effect due to imperfect polarization extinction.

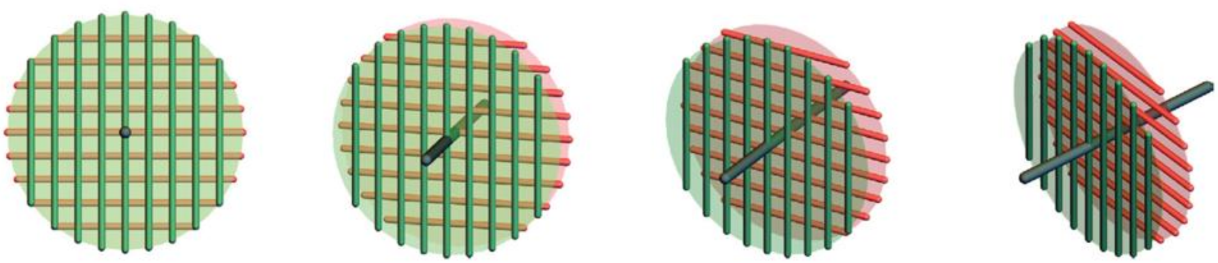

Figure 15: Two polarizers are crossed at 90 degrees with respect to each other. The polarizer in green has transmission axis at 90 degrees, while the polarizer in pink has transmission axis at 0 degrees. [Left to right] As the angle of incidence increases in 15 degree steps along the 45 degree azimuth direction, polarizer transmission axes are no longer perpendicular and allow light leakage. [3]

In a paper by Dr. Xinyu Zhu, this point is illustrated on the Poincaré sphere. Note, this scenario examines a 45 degrees-oriented crossed polarizer system, but shows the same principles as Figures 14 and 15. In the normal on-axis viewing position through crossed linear polarizers, the resulting polarization state (**T**) is at the same location as the analyzer (**A**). It is orthogonal to the polarizer absorption axis (**P**), so there is no transmission. [5]

However, part B in the figure presents an oblique view at 270 degrees where the polarizers are no longer orthogonal. As a result, the **P** and **A** have moved off the original location

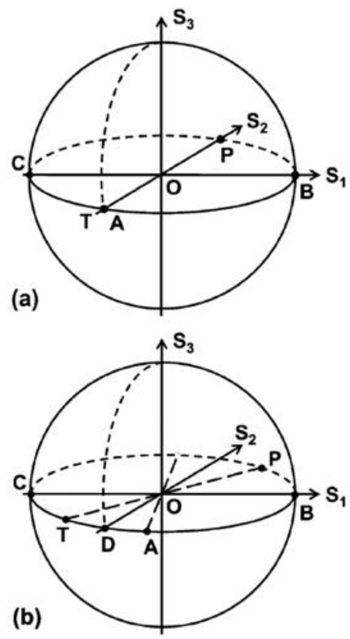

*Figure 16: The Poincaré sphere representation of a 45 degree cross polarizer system when viewed from [a] on-axis and [b] oblique viewing angle at 270 degrees off axis. There is a larger angle between **T** and **A** in [b] than in [a] which represents higher observed light leakage.*

*Plot notes: **P** is the polarizer axis, **A** is the analyzer axis, and **T** is the transmitted polarization state. **s1,s2,s3** are the Poincaré sphere axes. **B**,**C**, are the points of reference. **O** is the origin. A 550nm wavelength of light is considered. [5]*

and are no longer perfectly aligned. The resulting polarization (**T**) and analyzer (**A**) are also no longer overlapping and therefore indicates a light leakage and degradation of contrast.

In fact, the larger the angle of **T** to **A**, the worse the light leakage. Zhu notes this worst case occurs at the bisectors, or 90 degrees from the absorption axes. From these conclusions, engineers have identified that minimizing the **T** to **A** angle has the greatest potential to maintain the polarization state over angle. Hence, there is an advantage to optimize at the bisector angles which are the most affected oblique angles. [5]

Another factor not yet acknowledged in this discussion is the performance over wavelength. The polarization state is wavelength dependent and so additional studies must be done to improve the display performance as a function of the wavelength, or ideally the display's transmission spectrum.

To fully analyze the viewing angle property in LCD, all layers must be studied for their effects on viewing angle performance. The alignment and uniformity of all layers outside of the LC cell are crucial. For example, in the color LCD, there is a layer of red, green, and blue color filters in a matrix formation. If the color filter dimensions and thickness are not uniform or adequately separated from each other, there is a risk of color mixing from neighboring pixels. For example, one consequence could be that a 100% red pattern would inadvertently also have leakage of green or blue. Therefore, all layers beyond the polarizers can affect the outcome for color LCD.

In conclusion, two root causes are explained to answer why TN-mode LCD has degraded viewing angle. The light path view at oblique angles experiences a different projection of the LC director and is degraded by crossed polarizer leakages. These contributions as well as retardance dispersion over wavelength need to be considered for improvements to LCD for wide angle application.

Optimizations In LC Modes and Materials to Solve Retardance Over Angle

The previous section discussed how retardance and light leakage had higher variation at oblique viewing angles. New innovations were demonstrated over the years to improve component-level materials, LC mode, and layout of the device architectures. One outcome was to introduce vertical alignment and homogenous alignment instead of twisted so that any LC rotation happens within the plane parallel to the photoalignment layers. This way, there is no change in effective birefringence at different viewing angles since every perspective experiences the same retardance through the cell. Therefore, it minimizes the light leakage and expands the viewing angle [5]. Some enhanced LC modes are vertically aligned nematic (VAN) that was developed in early 2000s, the patterned vertical alignment (PVA) produced by Samsung in 1996, and IPS developed by Hitachi in 1996 [3].

The vertical alignment mode is used in vertically aligned nematic (VAN) LC, patterned vertical alignment (PVA), and multi-domain vertical alignment (MVA) [5]. The LC layer has a negative dielectric anisotropy and is aligned vertically at the off state [3]. Unlike the TN-cell, the off-state is the dark state condition. The VAN is better at maintaining the dark state over angle since the LC cell has zero retardance at this vertical state. When the electrical signals are switched on, the LC directors rotate in the x-z plane and produce the bright-state. There are multiple fringe fields that generate a symmetric viewing angle. It still suffers from the effect of the imperfect crossed polarizer leakage over angle, however.

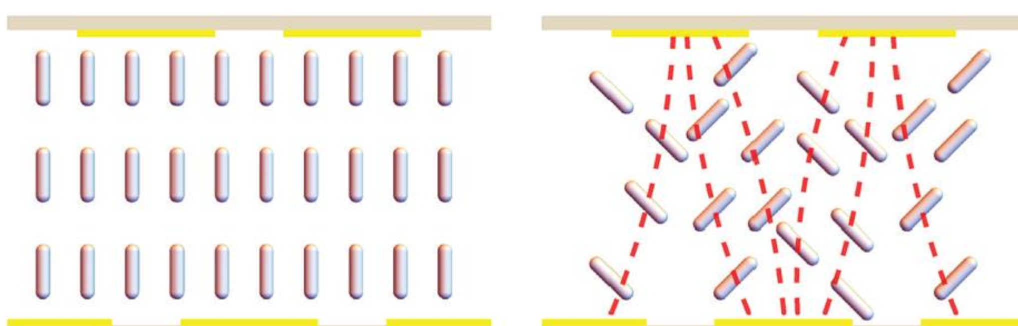

Figure 17: Vertically aligned nematic (VAN) type is shown. The yellow electrode pads are offset across the LC cell. [a] In the off state, the LC is vertically aligned; there is no twist. [b] In the on-state, the LC rotate and the electric field paths are drawn in red. This type of LC mode is better at maintaining dark state over angle since the LC cell has zero retardance at the off state and rotates in plane at the on state. [3]

PVA solved additional optical challenges seen with VAN. If the LC molecule director is perpendicular to the alignment layer, there can be stability issues with the electrical driving. This can cause motion picture blur and image sticking. Samsung produced a solution that patterns the electrodes in a zig zag across the cell, so that the electrodes are not on top of each other. Furthermore, the MVA concept added height on the ITO layer that influence the starting alignment director of the LC molecule. [3]

Two other successful LC modes are in-plane switching (IPS) and fringe-field switching (FFS). The LCs are homogenously aligned. At zero voltage, there is an off state. As the voltage increases, the directors rotate in the x-y plane to 45 degrees with respect to the polarizers. This creates a half wave of retardance condition resulting in the bright state. The mechanism for this driving is different than VAN because of the electrode placement. With IPS, the two electrodes are on the same side plate. Further development resulted in a Super-IPS, which generated a wide viewing experience to 178 degrees and low color shift over angle. Overall, IPS yields acceptable contrast for most applications from medical to consumer electronics, high pixel densities, insensitivity to external forces due to touch, and acceptable view angle. Some modern products include high-end tablets, smartphones, and Apple's Retina displays. [3]

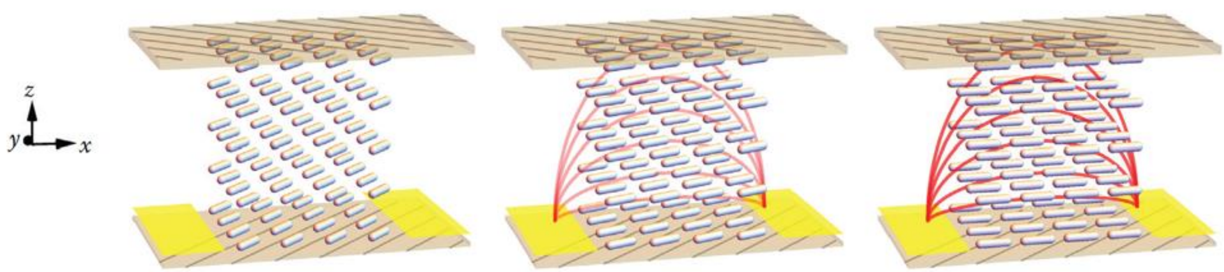

Figure 18: Schematics of the In-Plane Switching (IPS) where polarizers are oriented at 45 degrees. [Left] The figure illustrates the off state. [Center] The voltage is turned on and begins to influence the LC to rotate in the x-y plane. Red lines indicate the electric field. [Right] At full voltage, the on-state is exhibited. Red lines indicate the electric field. [3]

The data simulations in Figure 19 show quantitatively how advanced LC modes maintain the contrast out to an addition 10 degrees and is more symmetric [9]. Yet these improvements on IPS come at a cost. IPS requires advanced manufacturing processes and higher system power [3]. Different designs may offer better electrode designs to improve deficiencies in response time and image sticking. There can still be disclination issues in the actual IPS rotation because of the

LC molecules anchored on the top and bottom alignment layers [7]. Therefore, clear user requirements and documented tradeoffs are imperative when selecting the LC mode and architecture.

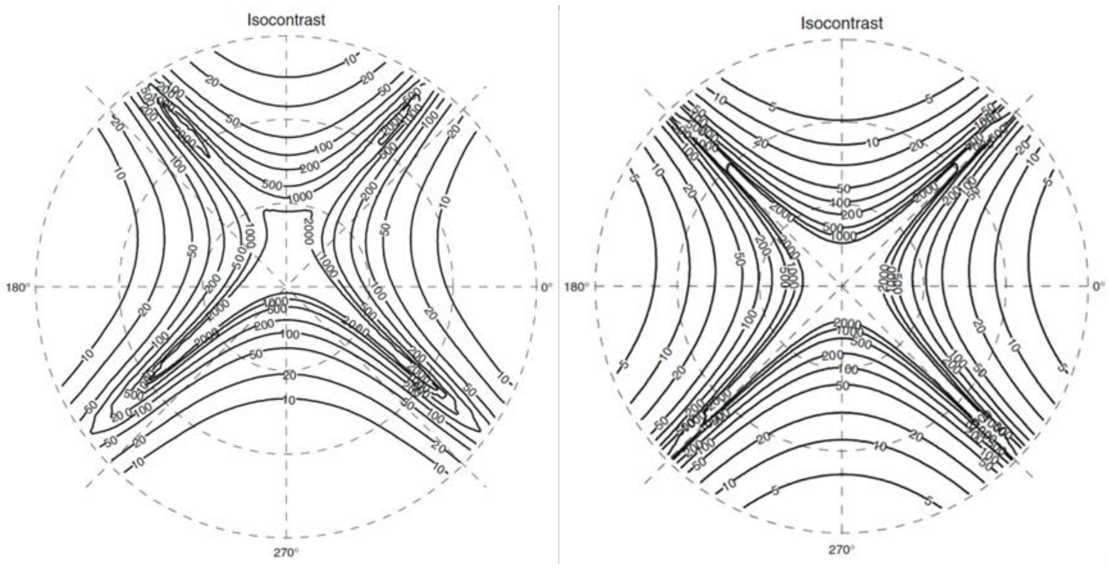

Figure 19: Isocontrast plot for [Left] TN-display and [Right] VAN- display. The VAN is more symmetric than the TN and maintains the on-axis contrast over a larger area for all azimuth directions.
Plot notes: The simulation assumes a crossed polarizer configuration at 45 degrees, so the worst contrast is at the bisector angles {0, 90, 180, and 270 degrees}. The polar plots are shown with θ=0-60 degrees polar and ϕ=0-360 deg azimuth. [a] is shown for λ=633nm and [b] is shown for λ=540nm. [9]

Optical Compensation Films to Solve Polarizer Leakage

The previous section highlighted new LC cell configurations introduced in the 1990-2000s to solve issues with the TN-LC mode. As a result, one promising architecture was the IPS mode, which minimized the change of birefringence as a function of angle since the liquid crystal switches in plane. Still, LCDs have inherent angular polarization aberrations; polarimetry methods can quantify how retardance varies as a function of the angle of incidence, and by extension, how the resulting polarization state will also vary with angle [3]. The effects of several degrees of retardance over angle and wavelength can lead to transmission and color variations, causing obvious brightness and color issues for LCD if left unresolved [3]. Luckily, further research has unlocked hardware solutions in a small, thin form factor to quantitatively compensate for known angular polarization aberrations. Thus, optical compensation films are a next-level strategy for the view angle deficiencies in LCDs.

Compensation films, also known as field-widening films, are made of molecules that are discotic, named after their disk shape. The molecules are engineered to cancel the retardance aberration for a specific layer of LC cell, typically by pairing the two layers with opposite eigenpolarization [3]. The below figure shows how layers of discotic compensation film can surround the LC cell to modify the polarization state in and exiting the LC. The compensation films can vary in thickness from ten to hundreds of microns.

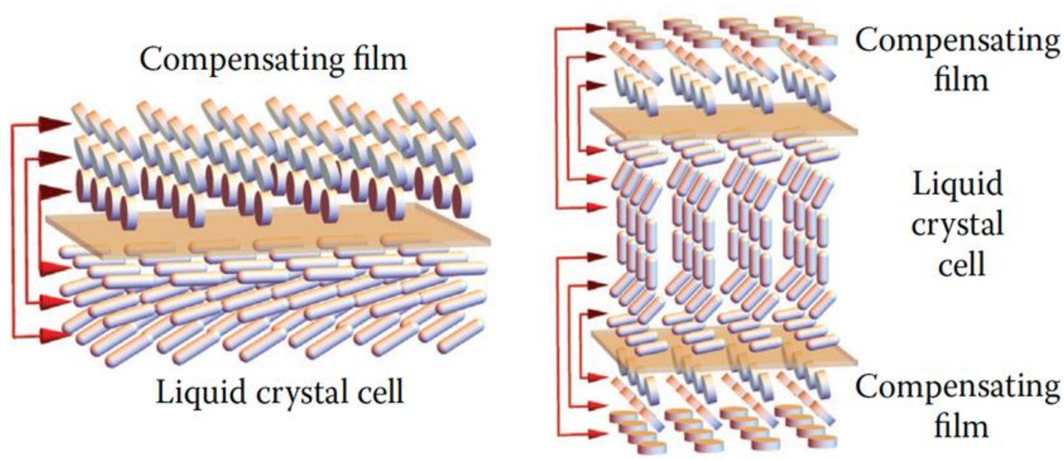

Figure 20: [Left] A schematic is shown of a compensation film made of discotic LC layered onto a LC cell. Each layer of compensation film corresponds to a specific layer in the cell. [Right] A compensation mode is shown on the top and bottom of the cell. [3]

With various design spaces for LCD, there are many groups of films that function as retardance compensators. Such films can be categorized as uniaxial or biaxial, named for the number of axes. Uniaxial films can further be categorized as *a*-film or *c*-film, depending on whether the optical axis is parallel or perpendicular to the film surface, respectively. Finally, the film can be positive or negative type, depending on the Δn, or the refractive index ratio of the extraordinary, n_e, to ordinary, n_o. The general convention is that a positive uniaxial film has $n_e > n_o$, while negative has $n_e < n_o$.

For a *c*-film, the optical axis is perpendicular to the surface of the display. It is appealing for LCD effects as a function of angle because the film is symmetric for all azimuth angles. This is appealing in design because the same compensation can be applied to all azimuth angles and therefore maintain uniformity. In Figure 22, the effect of one type of compensation film is shown in simulation utilizing extended Jones Matrices to model a VAN type LCD with 45 degrees-oriented polarizers [9]. The goal of the film is to reduce the off axis transmission in the dark state, thereby increasing the overall contrast. The optical film is a discotic, uniaxial type with negative anisotropy and placed at the exit of the cell. It's designed so that the Δn and thickness, *d*, of the cell and LC cancel: $\Delta n_{LC} * d_{LC} + \Delta n_{compFilm} * d_{compFilm} = 0$ [9]. The below figures show the effect before and after applying the film. The dark state transmission is reduced by 100x at on-axis and by 10x at the most severe angles out to 60 degrees off-axis.

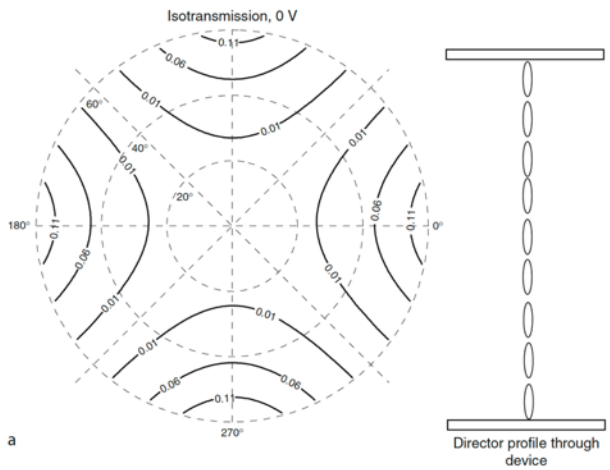

Figure 21: A simulated VAN type LCD shows the output isotransmission for the 0 V dark state at λ=540nm. The side view of the cell is shown at the right with no compensation film. [9]

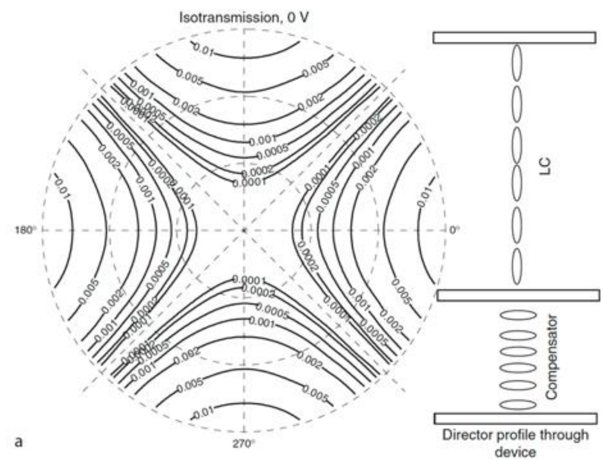

Figure 22: A simulated VAN type LCD has a uniaxial, negative anisotropic film. The side view of the cell is shown with the compensation film at the bottom of the LC. The polar plot shows the output isotransmission for the 0 V dark state at λ=540nm with a 100x decrease at on-axis and 10x decrease at off-axis compared to Figure 21. [9]

In another example, Zhu shows the uncompensated versus compensated contrast for an IPS-LCD. The approach is done with different configurations of uniaxial *a*-film and *c*-films with the goal to optimize for the highest, symmetric contrast across the field of view for maximum brightness. First, the uncompensated IPS-LCD yields a poor contrast of 10:1 at around 70 degrees off axis [5]. It is the worst at the bisector off-axis angles (0, 90, 180, 270 degrees) since this simulation is for a 45-degree oriented polarizer LCD. Zhu evaluates the many ways to compensate the IPS in simulation at λ=550nm. There are three varietals demonstrated: (I) one positive *a*-film and one positive *c*-film, (II) one positive *a*-film and one negative *a*-film, and (III) two positive *a*-films and one positive *c*-film. (In many of the cases, the same results can be obtained by using the opposite signed film.) Each case follows certain design rules about film stack and orientation. The films sandwich the LC cell, while the *a*-films are oriented parallel or perpendicular to the absorption axes of the polarizer and analyzer (but are always perpendicular if placed adjacent). The final design rule is the LC and alignment direction should be parallel to the first polarizer. These will ensure the films do not significantly degrade the on-axis transmission while trying to boost the off-axis. [5]

The figure below shows the results for case (II) one positive *a*-film and one negative *a*-film and illustrates the orientations of the films with respect to the BLU, the polarizer, LC rubbing direction, and analyzer. The Poincaré sphere shows the polarization state for the light propagation; it is a helpful tool to understand why the off-axis dark state improves so much in this condition. Theoretically, the dark state would attenuate all light leakage if the transmission state, **T**, was aligned to the analyzer, **A**. However, there is a gap. To get to **A**, the light utilizes *a*-films to rotate the polarization state from **T** to **E**, and then **E** to **A**. Now, the state is aligned to the analyzer absorption axis and the light leakage is minimized.

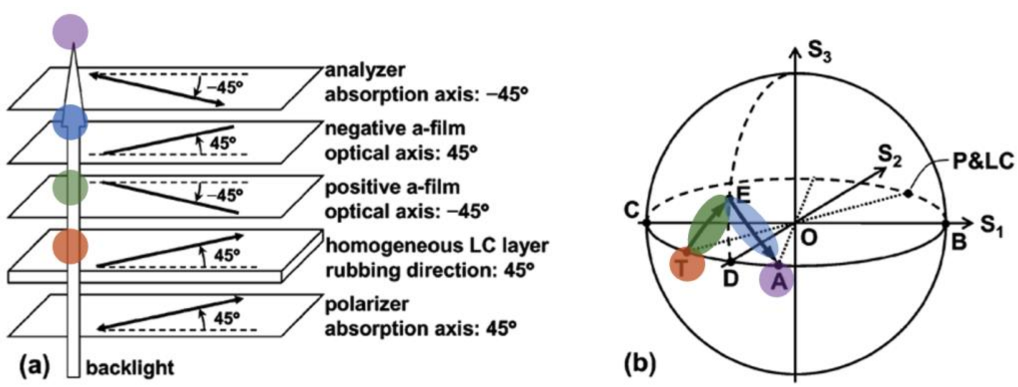

*Figure 23: [a] The display configuration for case (II) is shown with one positive a-film and one negative a-film. Note the careful orientations to the polarizer, LC rubbed alignment, and analyzer. [b] The Poincaré sphere shows the polarization state of the polarizer, **T** (shown in orange). The positive a-film rotates the polarization state from **T** to **E** (shown in green) and the negative a-film rotates the polarization state from **E** to **A** (shown in blue). The final polarization state is at point **A** (shown in purple) and is aligned to the analyzer absorption axis. Therefore light leakage is minimized. [5]*

The below are isocontrast plots for cases I, II, and III that compare which configuration yields the best contrast. The simulated plots are benchmarked against an uncompensated IPS-LCD in Figure 24. The contrast is 10:1 at the highest angles near 70 degrees. With a positive *a*-film and positive *c*-film added, the Figure 25 shows how case I is a significant improvement at higher angles to at least 100:1 at all angles, but lacks symmetry. Figure 26, however, shows case

II, a similar contrast performance at 300:1 at all angles and provides equivalent values at 30, 120, 210, and 300 degrees azimuth. This approach is improved yet again for case III in Figure 27 where the contrast has improved to 500:1 at 135 and 315 degrees azimuth, but is not symmetric in the other direction at 45 and 225 degrees azimuth.

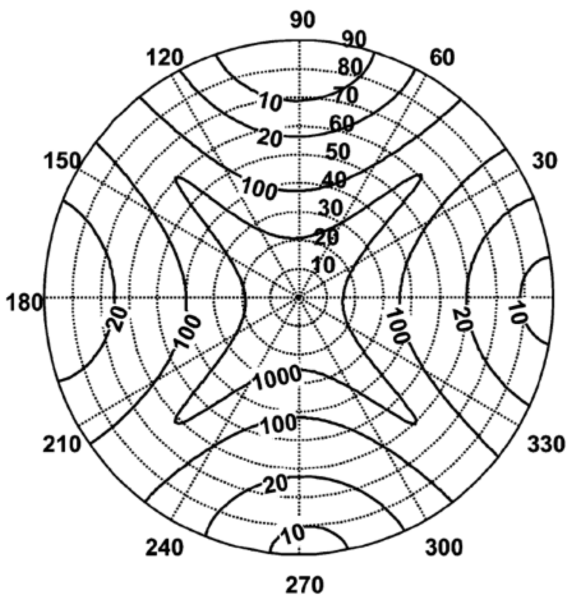

Figure 25: [Uncompensated] The iso-contrast plot is simulated for an IPS-LCD with no compensation film at λ=550nm. [5]

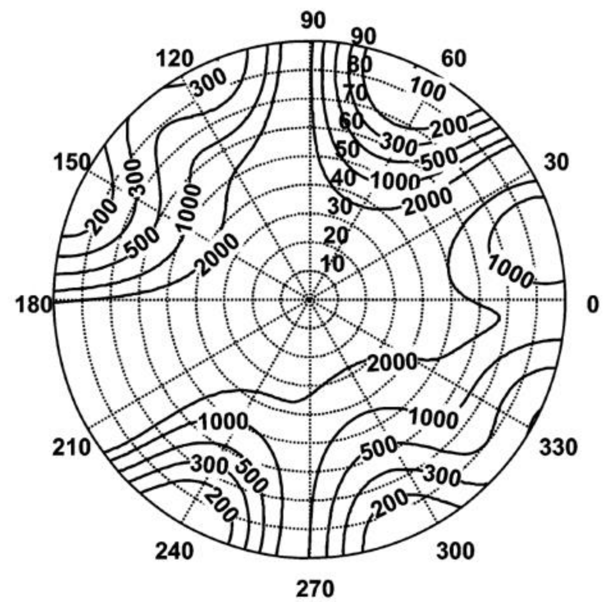

Figure 24: [Case I] The iso-contrast plot is simulated for an IPS-LCD with positive a-film and positive c-film at λ=550nm. Contrast is improved 10x and is >100 at all angles. [5]

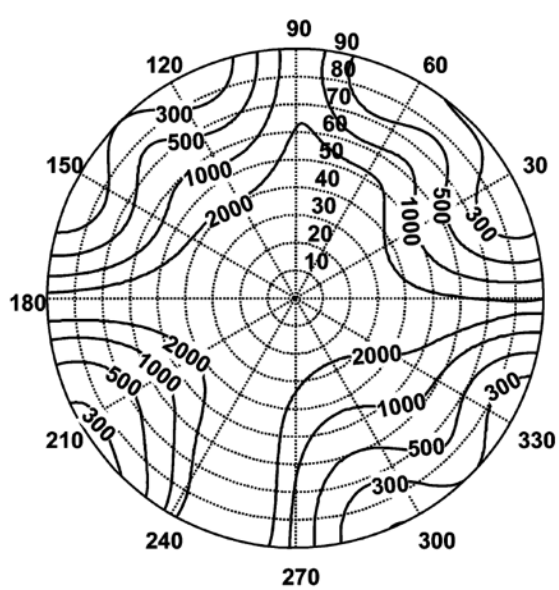

Figure 26: [Case II] The iso-contrast plot is simulated for an IPS-LCD compensated with one positive a-film and one negative a-film at λ=550nm. Compared to Case I, the contrast has doubled at the widest angles and is more symmetric. [5]

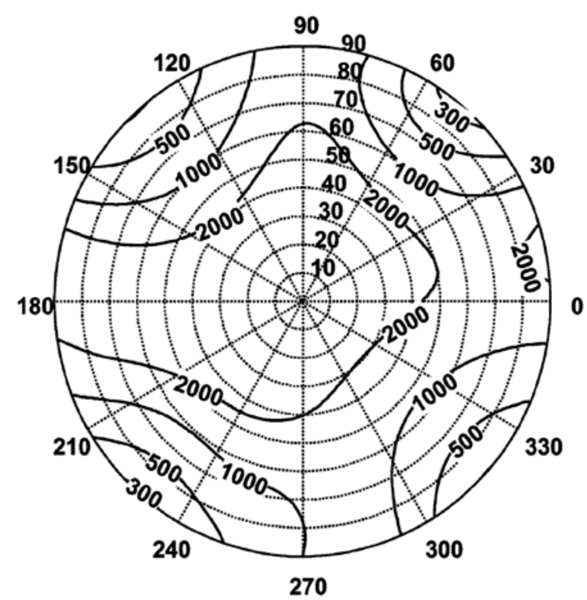

Figure 27: [Case III] The iso-contrast plot is simulated for an IPS-LCD compensated with two positive a-films and one positive c-film at λ=550nm. Compared to Case II, the contrast is increased to >500:1 on the 135 degrees and 315 degrees azimuth, while sacrificing the symmetry. [5]

Considerations for Off Axis Color

It's important to note that the above isocontrast plots are shown for a monochromatic wavelength at λ=550nm, so it does not fully characterize a color display. When considering compensation films for RGB displays, a system-level analysis on the visible spectrum is important to estimate the required retardance delta to balance the overall system. This is an issue because of inherent retardance dispersion since there is larger retardance in the blue wavelengths, yet smaller retardance in the red [3]. Luckily, displays are viewed by human eye, which has a peak photopic response at 550nm, so the previous simulations were optimized toward this value [5]. Yet, any leakage that is not fully compensated can escape as an undesired color. Figure 28 compares the off axis color emission for a TN and IPS display on a polar plot of rendered colors [11]. The IPS display has brighter transmissions at higher angles than the TN, but the IPS has obvious color variation at higher polar anlges and across azimuth. A more complicated film structure can solve these issues, yet there are tradeoffs. Adding numerous compensation films to cover all wavelengths and angles can increase cost and lower production yields due to complex construction and tighter cosmetic specification while sacrificing overall transmission [10]. In summary, the design constraints must be carefully considered for analysis over the visible spectrum.

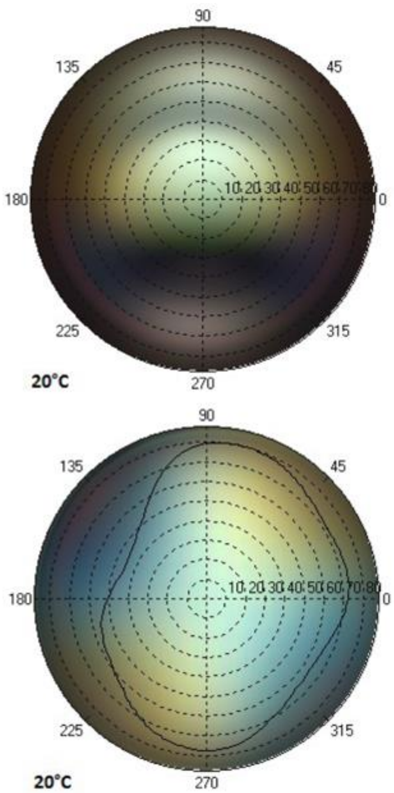

Figure 28: Renderings of color measurements that illustrate a Gray 128 pattern on a polar plot for [top] TN-display and [bottom] IPS display. The contour line in IPS is for 10 cd/m^2. Note the increased luminance and color variation over angle for IPS. [11]

Compensation Film Validation

When validating compensation films, one can utilize the Michael-Levy interference color chart to estimate the retardance in nanometers. The chart reports the linear relationship between the thickness of the material (in mm) to the amount of retardance (in nm). The slope of the line is determined from the material birefringence. The element under test is studied between a crossed polarizer linear polariscope with white light illumination. The output color observed through the polariscope can be located on the chart, which reports the thickness and therefore nanometers of retardance. The chart's relationship works because at a full 1 wave of retardance, the color at that wavelength is extinguished, leaving the viewer to see the other remaining colors. For example, at 550nm wavelength, all green contributions are extinguished, resulting in magenta outcome. If magenta is seen through the polariscope, the film under test has a retardance of 550nm; the actual thickness of the film is dependent on the birefringence. [3]

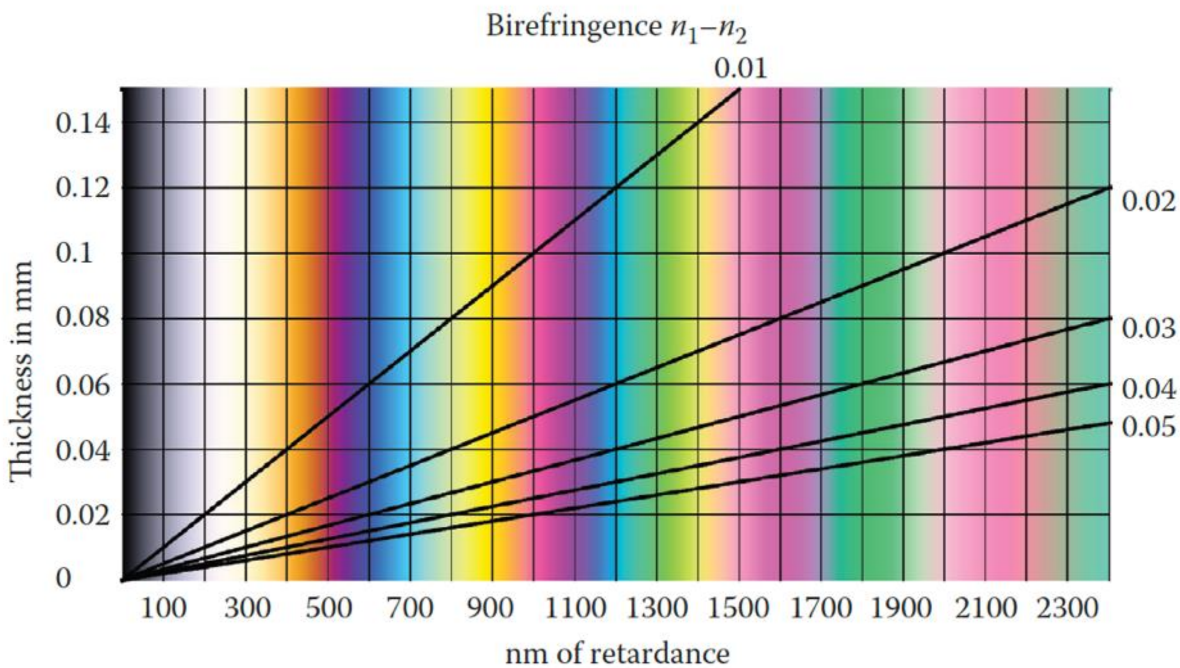

Figure 29: The Michael-Levy interference color chart is a plot of the thickness in mm versus the retardance in nm. It is useful in film metrology to measure the thickness based on the output colors observed through a polariscope with white light illumination. Any delta in the thickness can cause errors in the retardance. [3]

Prism Films to Boost Off Axis Distribution

While the above compensation films aid the angular performance within the panel layers of the LCD, there are additional groups of optical films that rely on other mechanisms to boost the off-axis light in LCD structures. Some examples worth introducing are prism films like in brightness enhancement films, reflectors, and polarization recycling films. They are manufactured to a high yield and used as modern solutions to increase the brightness of LCD backlights without additional power. For example, in a laptop with an optimized BLU, there is a 25% power reduction since fewer light sources are required in backlights which saves energy to drive and cool the sources for temperature stability. Overall, displays are now more efficient and offer longer lifetimes as a result [10].

The efficiencies with films were pioneered by 3M and include the brightness enhancement film (BEF) film and Dual Brightness Enhancement Films (DBEF). The films are engineered to emit a concentrated angular distribution of light with specific prism structures in the film. The prism is engineered to a specific cutoff angle that can transmit or reflect an incoming ray depending on its incident angle. As a result, the angular distribution can be specified so light can be maximized at desired angles and extinguished at others. A series of prism layers can also enhance the angular output. [10]

The beauty of light recycling further increases efficiency by manipulating the reflected beams. After the ray is reflected via total internal reflection (TIR), it propagates back through the substrate and returns to the backlight, usually to a reflector layer. The returning ray is reflected back so that it has another chance to emit at the designated output angle. As in the figure 30c, the recycling can also occur when the ray TIRs from a neighboring prism structure. Utilizing these designs can increase the on-axis luminance by 200% without the need for brighter sources. [10]

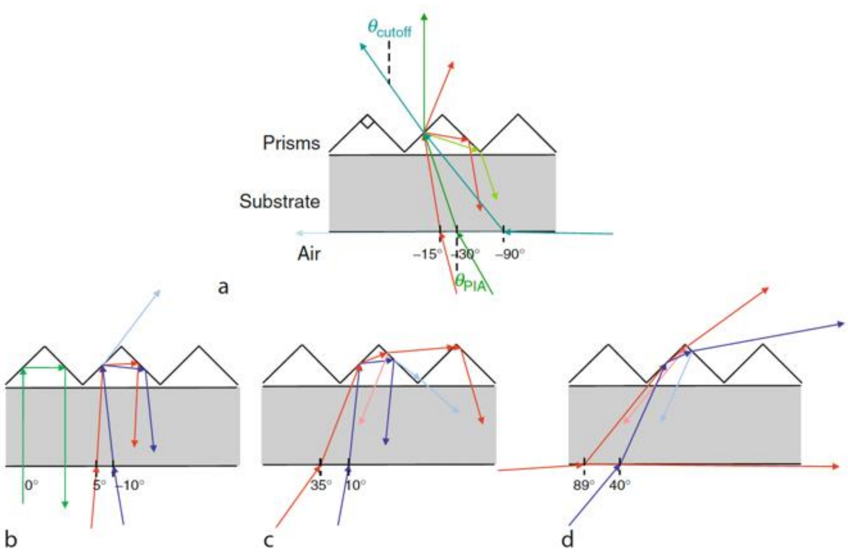

Figure 30: Diagrams of a prism film for a Brightness Enhancement Film (BEF) show (a) the engineered cutoff angle for maximum viewing and the resulting rays that follow total internal reflections (TIR) to return to the backlight. (b) The rays incident from certain angles follow TIR. (c) Some angles that exceed TIR exit the prism, but re-enter the neighboring prism feature and follow TIR to be recycled. (d) At high angles of incidence, the prism can be engineered to disperse light to larger angles. [10]

For polarization-sensitive LCDs, this reflection layer utilizes a Reflective Polarizer (RP) enhancement film in the backlight of the LCD. The purpose is for light recycling by the polarization state. One example design of a RP receives incident unpolarized light from the backlight and transmits light with the aligned polarization state to the polarizer, while reflecting the orthogonal polarization state. The film is placed before the first polarizer, so light that would otherwise have been absorbed by the polarizer, is instead reflected back to the backlight components. A series of reflections in the backlight further depolarize the light so that a reflection back toward the RP will restart the process again. Approximately half of the light has a polarization state aligned to the polarizer and the rest is reflected toward the backlight again. Effectively, this is a theoretical gain of 2x transmission, but in practice, the gain is 1.6-1.7x when factoring in losses due to Fresnel reflections, film absorption, scatter, imperfect reflection coatings, and others [11]. Figure 31 shows the effect of prism films quantitatively in a heatmap of the luminance over angle.

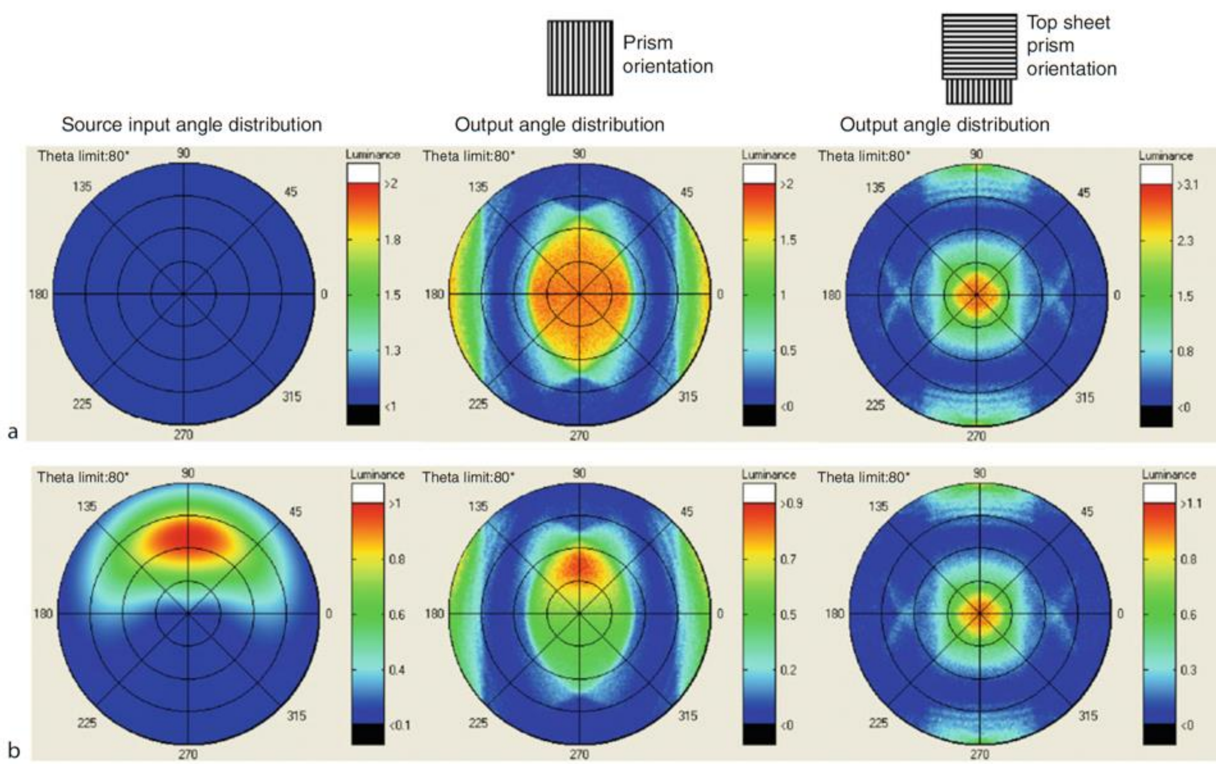

Figure 31: The three angular profiles for luminance distribution (normalized units) are shown for (row a) LCD backlight with inherent Lambertian profile and (row b) LCD backlight with side-lite lightguide and diffuser. By adding a prism film, the luminance increases up to 2x and light output cone has narrowed. With the addition of a second prism film, the luminance profile further increases relatively and also shows more concentrated light output at +/- ~35 degrees polar. In (b), the introduction of prism films has also shifted the profile toward on-axis, which is a similar distribution as (a). [11]

Conclusion

The progress of wide-viewing angle liquid crystal displays (LCDs) is a narrative that spans over 50 years and many technology iterations. A simple LC light modulator has evolved to the high-performance display seen in today's cell phones, televisions, and near-eye displays. These displays are the result of successful inventions and mass production developments in components such as birefringent materials like liquid crystals, LC cell modes, and polarization optical films.

LCDs utilize a liquid crystal cell as an illumination switch to modulate the light output. In a Twisted-Nematic (TN) structure, the liquid crystal will untwist with applied voltage and extinguish light, resulting in a tunable light output. The TN-LCD was the first successful commercial LCD product, one of which was used in Sharp's pocket calculator in 1973. Such a display refreshed information faster and with more power efficiency than prior designs.

Applying TN-LCD in more complicated applications proved to be a challenge for desktop monitors and televisions that required a consistent view angle experience. The TN-LCD brightness across the horizontal and vertical viewing directions degrades from the on-axis performance due to (1) birefringence in the LC cell and (2) the crossed polarizer light leakage at different viewing angles. As a result, the viewing cone is narrow and asymmetric with a leaky dark state. Instead, novel LC modes like VAN- and IPS-type minimized issue (1). Issue (2) was addressed by configurations of optical compensation films like *a*-films and *c*-films. The enhanced broadband view angle contrast performance was improved from 10:1 to >300:1 out to +/- 80 degrees off-axis. Overall, an adequate view angle performance for LCD was realized.

The developments described here are a few of the many that unlocked displays as functional opto-electrical devices for many applications. Viewing angle considerations are now a carefully specified engineering requirement with many optical strategies available to improve or compensate luminance profiles over the visible spectrum.

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