Display system analysis with critical polarization elements in a non-sequential ray tracing environment

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ABSTRACT

Common digital display systems have evolved into sophisticated optical devices. The rapid market growth in liquid-crystal displays makes the simulation of full systems attractive, promoting virtual prototyping with decreased development times and improved manufacturability. Realistic simulation using commercial non-sequential ray tracing tools has been instrumental in this process, but the need to accurately model polarization devices has become critical in many designs. As display systems seek more efficient use of light and more accurate color representation, the proper simulation of polarization devices with large acceptance angles is essential. This paper examines non-uniform polarization effects in the simulation of modern display devices using realistic polarizer and retarder models in the ASAP® non-sequential ray-tracing environment.

Keywords: polarization, non-sequential, ray-tracing, display, LCD, polarizer, liquid crystal, retarder

1. INTRODUCTION

In designing Liquid Crystal Display (LCD) systems, there are inherent light losses that must be controlled. Unlike the phosphors of traditional cathode-ray tube (CRT) displays, the liquid crystal (LC) picture elements are not emissive, so an auxiliary light source is used to illuminate them.

Most LCD units are lit from the back, and are thus called backlit displays. This component is generally characterized as a flat, transparent light guide that is illuminated by fluorescent lamps or light-emitting diodes. It must distribute light across the entire display surface, which involves both spreading the light from the sources throughout the guide, and coupling the light out of the guide and into the liquid-crystal structure. In illumination engineering, the design of backlight units has been widely practiced. This process is readily and commonly accomplished by non-sequential ray-tracing tools. The design of the liquid crystal panel depends on an adequate backlight design, and has typically been a separate, specialized design task.

As ray-tracing tools gain complexity, it is possible to evaluate the liquid crystal design using the same tools employed in the illumination design. While the role of polarization in the backlight design is limited, the liquid crystal panel design process includes critical polarization devices. Since the liquid crystal cells, the individual devices that drive each pixel of the display, are themselves polarization modulation devices, this is not surprising. In addition to the light-modulation devices, there are other important components in systems. Polarizers are necessary in virtually all designs. Retarders are important in many designs, particularly in providing compensation for polarization non-idealities that limit performance. Finally, the capability to describe complicated assemblies of these devices in a unified manner can simplify design by providing common building blocks, in a way analogous to describing a complex multi-layer interference coating by its design objective, rather than by enumerating all of its layers. In the Advanced System Analysis Program (ASAP®), realistic polarizer models (RPM) and realistic retarder models (RRM) have been implemented to accomplish this. With these devices descriptions, virtually all LCD designs can be analyzed.

It is also important to be able to examine radiometry and polarization for light at various locations in the system. In either case, numerical or graphical data may be used. Further, numerical data may summarize the entire light field of a display screen, or might bear information about an infinitesimal part of it.

The radiometry usually is evaluated in terms of display irradiance, radiance, or radiant intensity output. For example, the variation in intensity might be examined as a function of the viewing angle, the angle from the display normal...
direction. If human visual perception is factored into radiometry, then a photometric description is obtained. This might include, for example, the perceptual whiteness of a display or the variation in color at various parts of the screen.

Polarization analysis is critical when the initial design does not achieve the desired radiometric result. Since a final polarizer may destroy the information about polarization states in the system, it is necessary to be able to examine the states elsewhere in the system. This allows the designer to diagnose problem areas in the design and to correct them.

Given tools capable of describing the entire LCD system, it will be possible to optimize the entire system. This should lead to improvements in design efficiency. Not only is the design process more efficient, but it should also improve time to market for new products by reducing the need for prototyping, and by improving initial manufacturability. By integrating the design process, many design goals such as directional output or energy efficiency may be more readily optimized.

### 2. POLARIZATION OPTICS IN LIQUID CRYSTAL DISPLAYS

An image is displayed on an LCD by selectively switching devices corresponding to the individual picture elements, or pixels, of the device array. Each device contains multiple polarization elements that contribute to the performance of the system. Since this paper seeks to promote display analysis techniques to traditional optical designers rather than display specialists, it is useful to describe some of the basic elements and their functions in the system.

#### 2.1 The Liquid Crystal element

In an LCD, of course, a liquid crystal device is the fundamental building block. This device is often referred to as a “liquid crystal cell.” The liquid crystal class of materials is optically anisotropic, and responsive to an applied electric field at relatively small potentials. This effect allows them to alter the polarization state of transmitted light in a controlled fashion. The birefringence of the material does not, in general, have a fixed optic axis as a uniaxial crystal material does. Common LC materials may be treated as uniaxial materials with a variable optic axis alignment. There are numerous alignment schemes used in commercial displays, but detailed discussion of these is beyond the scope of this paper.

This work will consider a twisted nematic (TN) LC cell operating in normally-white (NW) mode, meaning that the cell passes light in its un-driven state. This scheme uses a cell that rotates an input linear polarization state 90°, resulting in transmission when placed between crossed polarizers. When a potential is applied to the LC material, its alignment is altered so that the transmission is reduced. Ideally, transmission of the input linear polarization state to the output side would occur, resulting in extinction by the second polarizer. The actual performance of the system will examined later.

#### 2.2 Polarizers

Fixed polarizing elements are essential to the switching function of a LC cell. The ideal polarizer passes light whose electric field is aligned with its transmission axis, and completely eliminates the orthogonal field component. This ideal construct has been useful for many analyses. Real polarizers depart from the ideal in several ways. One critical issue is that real polarizers do not exhibit complete extinction. Further, the extinction varies with the angle of incidence. In systems with highly divergent radiation patterns, as is typical of LCD systems, this is a key factor in system performance.

The most common polarizers in display technology are dichroic devices. They are birefringent devices that selectively absorb one of the two orthogonal polarization states that propagate in them. The Polaroid polarizer is a common example of this type, in which microscopic absorbing crystals are selectively aligned in a polymer matrix. There are two important classes of dichroic polarizers, distinguished by the mode of transmission. Since they are anisotropic, there is an ordinary and an extraordinary component. Polarizers that selectively transmit the ordinary component are called O-type polarizers. The complementary case is called E-type polarizers, which preferentially transmit the extraordinary component. Both of these cases are readily described using the RPM model in ASAP®.

In applied polarization analysis, it is useful to compare the result with analytical results. A useful test case is that of the transmission, T, of natural, randomly polarized light through a pair of crossed high extinction ratio O-type polarizers given by

\[ T = \frac{1}{2} \left( 1 - \frac{1}{R} \right) \]
\[ T = 0.5 \frac{\sin^4 \theta \sin^2 \varphi \cos^2 \varphi}{(1 - \sin^2 \theta \sin^2 \varphi)(1 - \sin^2 \theta \cos^2 \varphi)}, \]  

where \( \theta \) is the internal angle relative to the optical symmetry axis, and \( \varphi \) is the azimuthal angle about the axis. This is a common figure in polarization optics – the so-called Maltese cross, to be examined as a simple, but critical, polarization analysis.

### 2.3 Retarders

Retarders are constructed to alter the relative phase of two orthogonal linear polarization states. These are usually composed of uniaxial material with the optic axis in the plane of the device. Light with an electric field vector perpendicular to the optic axis experiences the ordinary refractive index, while light with its electric field aligned to the optic axis sees the extraordinary index. This difference determines the performance of the retarder. When this index difference produces a quarter-wave of phase difference, the device is a quarter-wave plate. The off-axis behavior is described in classic texts\(^2,3\), but it is sufficient in this work to say that it is well described by an extended Jones matrix method,\(^1\) which is implemented in the ASAP\(^\text{®}\) ray-tracing environment described here as the RRM.

Retarders may be used to compensate for the off-axis transmission of crossed polarizers, or for the birefringence of an LC device. In this application, we may call them compensators. We will examine one form of compensator in an LC device in one of the succeeding simulations.

### 2.4 Figures of merit

In displays, the performance has many potential measures. The overall brightness of the display is a typical figure of merit. Also, contrast is important, the contrast is determined by the ratio of the \textit{on}-state transmission to the \textit{off}-state transmission. The importance of this will become more apparent as we discuss analyses of LC devices in these operating states.

### 3. METHODOLOGY

To demonstrate LCD analysis using a non-sequential ray-tracing environment, several important aspects of polarization analysis need to be explored. Using the basic device elements described in the previous section, more complex, functional devices can be built and tested. These virtual prototypes, when applied in commercial settings, will help to reduce the need for time-consuming, costly, iterative design processes. The demonstrations include fundamental behaviors, since these can be verified simply, and more complex behaviors that may be compared to results of other analysis types outside the realm of non-sequential ray-tracing.

In all of these case studies, a reference radiant intensity is measured before interacting with the polarization device under test, and the final intensity is normalized by this result to obtain the transmission function. The resolution is chosen in each case to produce a reasonable noise level, and is controlled by the number of pixel defined in the measurement window. The coordinates used in all measurements are direction cosine coordinates A and B, which correspond to the direction cosines in the x-z and the y-z planes, respectively. In other words, A is the cosine relative to the x axis, and is thus the sine of the angle from the z axis in the x-z plane, and B is the sine of the angle from the z axis in the y-z plane. For those who are accustomed to seeing these data in polar coordinates, one noticeable difference is that direction cosine coordinates compress the results when far off-axis.

#### 3.1 Crossed polarizers

Using the relation of equation 1 for O-type dichroic polarizers, the result using the ray-tracing engine for a wide angular domain may be verified. A randomly polarized point source radiating into a cone of 80° semi-angle was used, with approximately \(4 \times 10^6\) rays. The polarizers were defined with an extinction ratio of \(10^{16}\) to facilitate comparison to the theoretical result. The transmission was evaluated by measuring the radiant intensity before passing through the device under test, and then normalizing the output by this reference intensity. The measurements were performed with a resolution of \(101 \times 101\) pixels, with nearest-neighbor averaging.
3.2 Crossed polarizers with enclosed C-plate retarder

This situation is modeled by inserting a wave plate between polarizers to produce a specified behavior. The wave plate being analyzed is a C-plate, which is a retarder whose optic axis is coincident with the system axis. A C-plate with 2.5 µm nominal retardance is inserted in the previous system. This is a simple example of a compensator. A randomly polarized point source radiating into a cone of 80° semi-angle was used, with approximately 2.5x10^5 rays. The measurements were performed with a resolution of 201x201 pixels, with nearest-neighbor averaging.

3.3 Normally-white twisted nematic liquid crystal cell in on state

Simulate an LC cell in its transmitting (on) state by enclosing a liquid crystal device between crossed polarizers. The polarizers are O-type. The LC is represented by a progression of sub-cells that describe the tilt and twist of the optic axis as a function of position along the propagation direction. The tilt is fixed at 2°, and the twist proceeds linearly from the first polarizer alignment to the second, through an angle of 90°. The transmission of the cell is analyzed by a wide-angle source to simulate the output of a backlight. This shows the maximum transmission performance of the system. A randomly polarized plane wave source was used to illuminate a lens to produce a beam with 74° semi-divergence, with approximately 3x10^6 rays. This beam was measured to provide a transmission reference, then passed through the device. The measurements were performed with a resolution of 101x101 pixels, with averaging over the nearest and second-nearest neighbors.

3.4 Normally-white twisted nematic liquid crystal cell in off state

This model differs from the on state model by the tilt and alignment of the optic axis through the LC cell. The LC in this case transfers little light in the output polarizer’s preferred state. This dark (off) state is important in the characterization of contrast of a display. The source strategy was the same as in the previous example, but with the number of rays reduced to about 8x10^5. The measurements used a resolution of 101x101 pixels, with nearest-neighbor averaging.

3.5 Compensated normally-white twisted nematic liquid crystal cell in off state

In this model, a retarder is inserted into the cell to compensate for the leakage due to birefringence of the LC cell. The compensator has a negative twist relative to the LC twist, and a negative retardance. The leakage reduction is examined. The source strategy and measurement strategy were identical to the previous example.

4. SIMULATION RESULTS

4.1 Crossed O-type polarizers

The transmission of the crossed polarizer system is shown in Figure 1. This result was compared to the theoretical result of equation 1, and found to deviate within computational limits. The most notable deviations were near the edge of the measurement window, and are probably due to edge effects in the measurement and normalization process.

![Figure 1](image)

Figure 1. Comparison of the ray-traced crossed-polarizer leakage to the theoretical result. The left figure is produced by simulation, while the right figure is a theoretical result from equation 1.
4.2 C-plate retarder between crossed polarizers

This is done to show how a retarder affects the crossed polarizer behavior. It is shown in Figure 2 for a 2.5 wave C-plate retarder with the same polarizer parameters as in the previous case. The retardance results in a ring structure of transmission minima and maxima due to the relatively large total retardance available to off-axis paths. The retardance on axis is zero, so the on-axis performance of the crossed polarizers is maintained.

![Figure 2. Leakage of a crossed O-type polarizers with a thick C-plate retarder inserted between them. Multiple nulls and peaks result from the off-axis retardance, while the absence of on-axis retardance retains the central null.](image)

4.3 NW TN-LC cell

The LC element is enclosed in the polarizers. The LC element is described by a series of 20 layers. The pre-tilt of the LC material is fixed at 2°. The twist varies linearly from the first polarizer alignment at 45° through to the second polarizer alignment at 45+90=135°. The transmission is shown in Figure 3.

This result compares well to results calculated using the extended Jones matrix method for an identical system. The peak transmission is somewhat less than 0.5, the theoretical limit for transmission through crossed polarizers illuminated by natural light.
The LC element is enclosed in the polarizers. The LC element is described by a series of 20 layers. The tilt and twist of the LC material is developed to represent the off state after Yeh. The transmission is shown in Figure 4. Note that the peak leakage is of the same magnitude as the on state transmission.

4.4 NW TN-LC cell in off state

The LC element is enclosed in the polarizers. The LC element is described by a series of 20 layers. The tilt and twist of the LC material is developed to represent the off state after Yeh. The transmission is shown in Figure 4. Note that the peak leakage is of the same magnitude as the on state transmission.

Figure 3. Transmission of a simple LC cell in the on state. The maximum transmission is slightly below 0.5. The illumination is relatively constant across much of the output hemisphere.

Figure 4. A normally-white LC cell in the off state. There is significant leakage inherent to the polarizer and the LC cell birefringence, reducing the contrast of the display.
4.5 Compensated NW TN-LC cell in off state

The LC element in its off state is compensated by a negative-twist, negative birefringence twin. Figure 5 illustrates a reduction of one order of magnitude in the transmission, a great improvement in leakage. This is a simple compensator design, but compensators can be composed of many layers. The goal is simply to match the selective orientation and state of the output polarizer.

Figure 5: A Normally-white LC cell with a negative twist, negative retardance compensator. The leakage is reduced by approximately one order of magnitude.

5. POLARIZATION SPECIFIC TOOLS

The simulations are based on well-known design principles. If undertaking new design goals, one may want to examine intermediate polarization states to decide how to improve a performance target. Using the un-compensated cell in its off state, examining the polarization state before the second polarizer may be useful. One might do this on an individual ray basis, observing individual polarization parameters such as ellipticity or orientation, or for a large ensemble of rays using graphical tools.

5.1 Numerical tools

When approaching a linear polarizer, the optimum result is typically achieved when the states to be analyzed are also linear. This is another way of saying that we usually want to optimize the on and off states. A simple examination of the ellipticity of states may reveal the need for additional compensation elements. This output should include information about the position, direction, polarization basis state, and polarization vector components of a ray under consideration.

5.2 Graphical tools

Visualization of states using a graphical tool is useful when there is a angle of states present, or when there is a process that is causing an undesirable splitting of states. One of the most useful visualization tools allows states to be depicted using the Poincaré sphere\(^5\). In the case shown in Figure 6, there are three distinct populations of polarization states, which also happen to have distinct wavelengths and ray flux ranges.

This is useful for diagnosing an unintended effect, for example a polarization anomaly in the illumination source or an element misaligned so that multiple paths through the system are possible.
6. CONCLUSIONS

Computational design tools have been important in the development of modern commercial optics. As optical practice spreads beyond the traditional optical design community, it is important that design tools develop the required scope. In the LCD industry, rapid development has called upon many engineers to integrate design functions that were previously the domain of specialists. As usual, software has been asked to compensate for the change.

Traditional optical software companies are responding to this need. Non-sequential ray-tracing has been used in the LCD area since its inception, but mostly for illumination design of backlight units. As the science and technology of polarization ray-tracing has evolved, the role of this practice in LCD design has expanded. As in many other optical systems, the ability to conduct all tasks of a design has been realized. True end-to-end analysis is possible with the addition of the necessary analysis of the front-end polarization components.

This capability will continue to evolve as new tasks are required and new design objectives must be achieved. A useful computational infrastructure is the first step, and new tools are under continual development.

REFERENCES