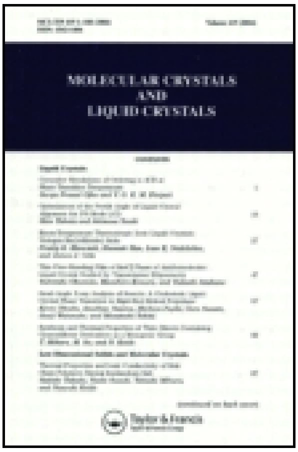

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Mark F. Flynn [a] & Phil Bos [a]
[a] Department of Physics and Liquid Crystal Institute, Kent State University, Kent, OH
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CONTRAST AND COLOR UNIFORMITY OPTIMIZATION OF AN LCD PI CELL PIXEL

Mark F. Flynn and Phil Bos
Department of Physics and Liquid Crystal Institute,
Kent State University, Kent OH

Abstract A recently developed numerical optimization procedure for liquid crystal displays, combining an accurate model of optical performance with a flexible and efficient parameter search algorithm via the maximization of a performance metric, is applied to a Pi (or bend) liquid crystal cell with uniaxial and negative birefringent compensation layers. Optimization is performed with respect to off axis contrast and white state color uniformity.

INTRODUCTION

Active matrix liquid crystal displays (LCDs) are becoming common place. On axis, these devices rival the optical performance of CRTs. Off axis, however, serious problems need to be overcome, two of which are loss of contrast and color nonuniformity. Both of these can be traced to the nonsymmetric nature of the twisted nematic (TN) LCD, the most commonly used liquid crystal (LC) configuration used.

Recently, various investigators have been looking at a very different LC configuration, known either as the Bend alignment, or Pi cell[1]. Unlike the TN cell, the LC in this configuration is confined to a plane, and acts as a voltage dependent tunable compensation film. Thus, if it is placed between two parallel retarders, and used in conjunction with a fixed compensation layer, it is possible to produce a device with a voltage-dependent transmission, much like a TN pixel. But since the LC configuration is much more symmetric, it is hoped that the viewing angle problem will be substantially reduced.

Bos [2] and Uchida *et al.* [3, 4] have looked at optimization of such devices, with promising results. In this paper, we apply a recently developed numerical optimization technique[5, 6] which optimizes with respect to a chosen performance metric, to this problem. Optimization is performed simultaneously with respect to both off-axis contrast and white state color uniformity. As optimization over many parameters is a complicated business, in this first application to the Pi cell device we make two simplifications. First, we will confine ourselves to uniaxial retarders. Second, we will for the moment neglect dispersion effects.

A word is in order concerning coordinate systems. All work is done using a Cartesian coordinate system, as shown in Fig. (2). The z axis is aligned with the direction of propagation of light directly through the pixel (on axis viewing), and the pixel is parallel to the xy plane. Both director configurations and viewing angles are given in terms of a polar (or tilt) angle, measured with respect to the xy plane, and an azimuthal angle, which measures rotations in the xy plane in a counterclockwise direction from the positive x axis.

After a brief discussion of the Pi cell and optimization techniques, we present the results, followed by a conclusion and future prospects.

THE PI CELL

In the TN pixel, retardation layers may be added in order to improve the viewing angle characteristics. In the Pi cell device, they are indispensable for correct optical functioning. In Fig. (1), we show the tilt angle of the LC director at $2V$ versus distance through the cell. The twist angle is zero throughout. Such a configuration is achieved by rubbing the two sides of the LC cell in the same direction.

Once we have the LC configuration set, it is placed between two crossed polarizers, as shown in Fig. (2). Thus, depending on the retardation of the LC, some amount of light will be transmitted through the pixel. At high voltage, the LC aligns with the field, and the retardation drops to zero, at which point all light is blocked. For intermediate voltages, the retardation will be between that of these two extreme values.

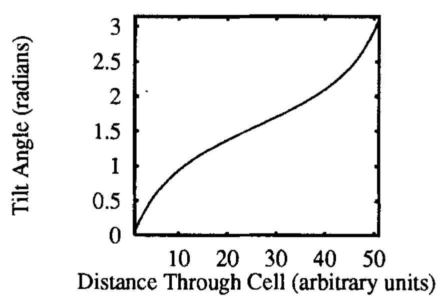

Figure 1 *The director configuration of the Pi cell with an applied voltage of* $2V$.

When we add a retarder with optical axis crossed with the rubbing direction of the LC, we achieve a black state whenever the retardation of these two layers are equal. Thus, by selecting the retardation of the compensation layer, we may select as black any voltage state we choose. The viewing angle characteristics of this configuration should be much better than that of a standard TN pixel, because of the "self compensation" of this device[2].

The above discussion is oversimplified. In fact, the bend configuration shown in Fig. (1) is not the only possible state given the boundary conditions. See Refs. [1, 4] for details. However, for the range of voltages considered in this paper, we may safely assume that this is the configuration of physical interest, or very nearly so.

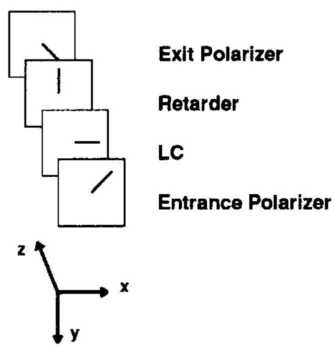

Figure 2 *Schematic representation of basic Pi cell pixel with crossed retarder element. Lines on each element indicate the direction of the optic axes.*

OPTIMIZATION USING PERFORMANCE METRICS

There are a large number of parameters (e.g., LC thickness, polarizer orientations, retardation values of compensation layers, etc.) which effect the optical performance of an LCD in highly complex and nonlinear ways. Thus, it is desirable to have a technique for optimizing the values of these parameters which is in some sense automated. This was precisely the motivation behind the optimization procedure first presented in Ref. [5], and which has been successfully applied to the optimization of a TN pixel, as well as been experimentally verified[6].

Briefly, the method consists of the following. We first define a performance metric, which is a mathematical function of our choosing that in some way describes the optical performance of the display. Consider the simple example

$$M = \int_0^{2\pi} d\phi \int_0^{\theta_{Max}} d\theta\, \theta\, C(\theta, \phi), \tag{1}$$

where $C(\theta, \phi)$ is the contrast at a given viewing angle specified by the azimuthal and polar viewing angles ϕ and θ. The larger the value of this function, the better, in some sense, is the display.

Next, we need a way to evaluate this function. Thus, we need an accurate and efficient numerical model to describe the display optics. This is done by solving the Frank free energy for the LC director configuration as a function of applied voltage, and then using a technique[7] derived from Berreman's 4x4 method[8, 9] to solve for the optical response of the display pixel. All modeling is done at the pixel level.

Finally, we must choose some set of parameters to vary. While more complete choices are clearly possible, in this paper we consider variations with respect to compensation layer thicknesses (which varies the retardation values) and orientations.

At this point, we have reduced the problem of LCD pixel optimization to that of maximizing the chosen performance metric with respect to the given set of parameters. There are a host of numerical methods to accomplish this task.

RESULTS: SIMPLE PI CELL PIXEL

The simplest Pi cell pixel is that shown schematically in Fig. (2). One places a simple uniaxial retarder at right angles to the LC rubbing directions, so that a black state is achieved for that voltage which produces a retardation in the LC equal to that of the uniaxial retarder.

For all of the results in this paper, we use a Pi cell with the characteristics described in Table (I), and a range of voltages between 2 and 6 volts. We consider pixels which are compensated such that the black state is at one of these two extreme voltages. The uniaxial retarder used has indices of refraction $n_o = 1.5$ and $n_e = 1.50286$, so that it has a retardation of $2.86/um$.

The first step in optimizing this simple pixel is to choose a metric. In the TN pixel work of Refs. [5, 6], good results were obtained with the metric

$$M_{550} = \int_0^{2\pi} d\phi \int_0^{\theta_{Max}} d\theta\, \theta\, min(R_{Max}, R_{550}(\theta, \phi)), \tag{2}$$

where R_{550} is the ratio of white state to black state transmission values at a wave-

Table I: *Characteristics of the Pi Cell used in all calculations.*

Elastic Constants	$k_{11} = 10.1pN$, $k_{22} = 5.6pN$, $k_{11} = 19.7pN$
Dielectric Constants	$\epsilon_{\|\|} = 15.0$, $\epsilon_{\perp} = 4.7$
Indices	$n_o = 1.493$, $n_e = 1.632$
Cell Thickness	$d = 9.5\mu m$
Pretilt Angles	$\theta_{pretilt} = 3^o$

length of $550nm$. Unlike the metric of Eq. (1), the integrand is chopped at a value of R_{Max} (here set to 20). If this is not done, solutions are found which have very sharp peaks in the contrast, and these are uninteresting. The parameter θ_{Max} is the maximum value of the polar viewing angle calculated, and is set to 40^o. Note that the above metric will produce nearly identical solutions to one which optimizes with respect to contrast, but with much less computational effort, as long as there is not too strong a wavelength dependence in the transmission.

Next, a set of parameters must be chosen over which to vary the metric. For this simple pixel, variations are performed with respect to the retarder thickness (which varies the retardation) and orientation in the xy plane. Starting points for the thickness parameters are chosen by setting the retardation equal to that of the on-axis LC retardation.

Table (II) shows the optimal values of these parameters for the pixel compensated at 2 and 6 volts. The retarder thickness to be expected by considering only on-line LC retardation values are $146\mu m$ and $47\mu m$, respectively. The optimal solutions found are different because we are optimizing $550\mu m$ transmission contrast over all calculated viewing angles. The effect of this can be seen in Fig. (3), which show the luminance versus voltage for the two optimal configurations. On axis considerations alone would require that the black and white states occur at the absolute luminance minima and maxima, respectively, but this is not the case.

Figures (4) and (7) show contrast versus viewing angle. Even for such a simple pixel, the viewing angle properties are very good.

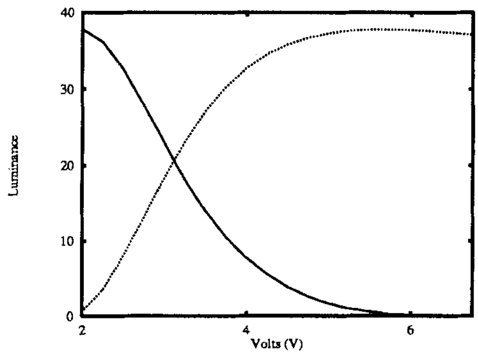

Figure 3 *On axis luminance versus voltage for the simple Pi cell pixel compensated at* $2V$ *(dotted line) and* $6V$ *(solid line). A spectral white light source of unit intensity was used.*

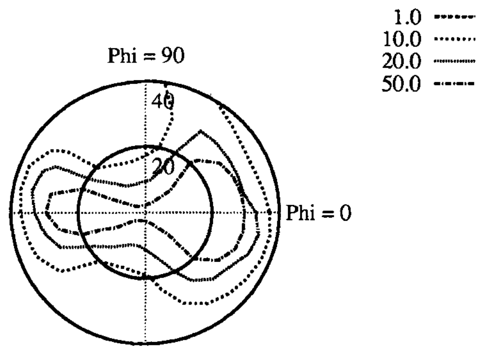

Figure 4 *Contrast versus viewing angle for the simple Pi cell pixel compensated at* $2V$.

RESULTS: PI CELL PIXEL WITH NEGATIVE BIREFRINGENT FILM

Next, we add a negative birefringent (NB) retardation film to the pixel, on the exit side of the uniaxial retarder. This film has values of $n_o = 1.5$ in the xy plane, and $n_e = 1.454$ along the z direction, and thus has a retardation of $-46/\mu m$. Because of its peculiar properties, it has almost no effect on the on axis optical behavior of the pixel, but a pronounced effect off axis. Optimization is now over the two parameters discussed above, as well as the thickness of the NB film.

Table (II) shows the optimal values of these three parameters, again for pixels compensated at 2 and 6 volts. Figures (8) and (9) show contrast versus viewing

Table II: *The optimized configurations for the various Pi cell pixel, compensated at two different voltages. Data is shown for a pixel with uniaxial retarder (Uni), with uniaxial retarder and negative birefringence film (Uni + NB), and the same, but optimized for contrast and color uniformity via the metric of Eq. (6) (Uni + NB + CIE).*

Pixel	Voltage (V)	2	6
Uni	Orientation	91^o	90^o
	Thickness (μm)	144.5	42
Uni + NB	Orientation	90^o	91^o
	Thickness (μm)	144	44
	NB Thickness (μn)	6.3	20
Uni + NB + CIE	Orientation		90.3^o
	Thickness (μm)		50
	NB Thickness (μm)		10.5

angle. The improvement in viewing angle is very impressive.

AN IMPROVED METRIC: COLOR UNIFORMITY

Figure (5) shows the CIE-1931 chromaticity coordinates as a function of viewing angle for the Pi cell with retarder and NB film, compensated at 6V. The 2V compensated cell shows a similar variation. While this is not a disastrous variation, we can certainly hope to do better.

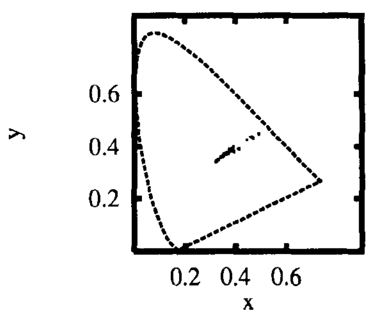

Figure 5 *CIE 1931 chromaticity coordinates for the Pi cell pixel with retarder and NB film, compensated at* 6*V. Data shown is for various azimuthal angles, at the maximum tilt angle of* 40^o.

In order to take color into account, we need some measure of "distance" between two colors. Somewhat arbitrarily, we have done this using the function

$$d_{CIE}(x_1, y_1, x_2, y_2) = ((x_1 - x_2)^2 + (y_1 - y_2)^2)^{1/2} , \tag{3}$$

where x, y are the CIE 1931 chromaticity coordinates. Given this, a simple way of reducing nonuniformity in color is to search for solutions which have the smallest variation in these coordinates over viewing angle. Consider the function

$$\bar{d}_{CIE} = \langle d_{CIE}(x_{av}, y_{av}, x_i, y_i) \rangle , \tag{4}$$

where $\langle\rangle$ implies an average over viewing angles, and x_{av} and y_{av} are the average values for the CIE coordinates. If there were no variation in color at all, $\bar{d}_{CIE}$ would be zero, and the larger its value, the more variation there is. This leads us to define another metric,

$$M_{CIE} = \frac{1}{\bar{d}_{CIE}} , \tag{5}$$

and the total metric over which we optimize is now

$$M_{CIE+550} = M_{550} * M_{CIE} . \tag{6}$$

With this new metric, the pixels were reoptimized. In evaluating the value for M_{CIE}, we only considered the optically on state at the maximum polar viewing angle used, namely 40°. This was done for computational efficiency, though it is expected that small variations in color at the extreme viewing angles will produce small variations for all viewing angles.

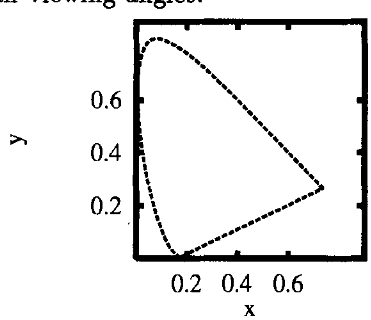

Figure 6 *CIE 1931 chromaticity coordinates for the Pi cell pixel with retarder and NB film, compensated at 6V and optimized for color uniformity. Data shown is for various azimuthal angles, at the maximum tilt angle of 40°.*

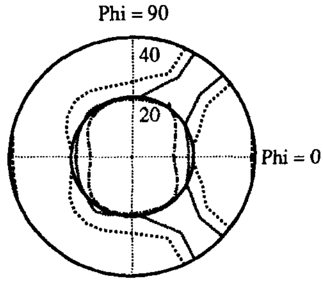

Figure 7 *Contrast versus viewing angle for the simple Pi cell pixel compensated at 6V. Contrast levels are the same as in Fig.(4).*

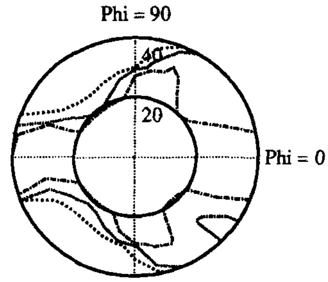

Figure 9 *Contrast versus viewing angle for the Pi cell pixel with NB film, compensated at 6V. Contrast levels are the same as in Fig.(4).*

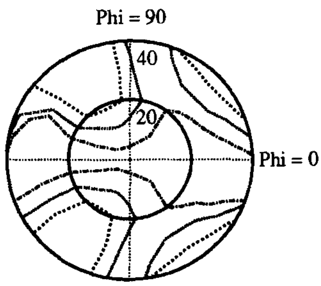

Figure 8 *Contrast versus viewing angle for the Pi cell pixel with NB film, compensated at 2V. Contrast levels are the same as in Fig.(4).*

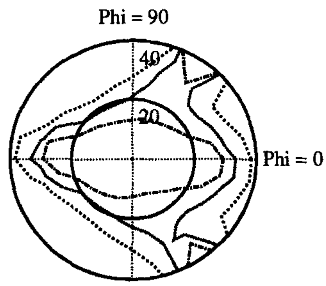

Figure 10 *Contrast versus viewing angle for the Pi cell pixel with NB film, compensated at 6V and optimized for color uniformity. Contrast levels are the same as in Fig.(4).*

Table (II) shows the optimal values of these three parameters for the Pi cell pixels compensated at 6 volts. Figure (6) shows the CIE-1931 chromaticity coordinates for the 6V optimized pixel, clearly showing a dramatic reduction in color variation. Since this data is at the extreme polar angles, the color variation for smaller polar angles is certainly even less.

Interestingly, for the 2 volt pixel, almost no improvement in color variation was obtained, and thus no results are shown

Figure (10) show contrast versus viewing angle. The reduction in color uniformity has come at some cost in contrast, though the pixel is still markedly superior in this regard compared to the pixel without the NB film shown in Fig. (7).

CONCLUSIONS AND FUTURE WORK

In this paper, we have considered the optimization of a Pi cell LCD pixel with various retarder configurations, and compensated to black at two different voltage states.

We have shown that this cell, compensated with a simple uniaxial retarder, can produce very good contrast over a wide range of viewing angles. Optimization was performed by maximizing a performance metric which measures transmission contrasts at a wavelength of $550\mu m$, and by varying the thickness and orientation of the retarder.

Next, a negative birefringence film was added to the pixel, which was then reoptimized with respect to the previous set of variables and the thickness of the new element. A dramatic improvement in viewing angle characteristics was obtained for both the high and low voltage compensated pixels.

Finally, we examined the color uniformity of the optimized pixel, and observed that it was less than ideal. A new metric was constructed which also took into account variations in CIE 1931 chromaticity coordinates over viewing angle. The pixels with uniaxial retarders and NB films were again reoptimized. For the $2V$ compensated pixel, almost no improvement was noted in color uniformity. However, for the $6V$ pixel, a drastic reduction in color variation was obtained. While this was accomplished at the expense of some loss in off angle contrast, the overall viewing angle characteristics were still very good.

The improvements in the Pi cell pixel off axis contrast shown here are similar to those discussed elsewhere[2, 3, 4], thought previous work has not considered the additional problem of color variations. In the near future we will extend this work to consider the sort of biaxial retarders utilized in Pi cell optimizations by Uchida *et al* [3, 4].

Once again, the performance metric optimization[5] technique has performed well. However, there are various improvements we will examine in the near future. First, while the color nonuniformity has been reduced, the final on state color is still slightly yellow. We will examine color metrics which favor configurations close to a chosen color, i.e., white. Second, we have completely ignored the important issue of gray scale, and we will extend the metrics discussed here to include the characteristics of intermediate voltage states as well. Finally, a more sophisticated metric for contrast ratio will be examined, which favors uniformity as well as increased values.

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