Optical Efficiency for Different Liquid Crystal Colour Displays

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HPL-2000-83
June 29th, 2000*

optical efficiency,
LC displays,
phase change,
birefringence,
polymer dispersed

There are at least 6 fundamental types of liquid crystal displays recorded in the scientific literature. Each type exhibits a different physical effect to generate a colour image on the display. It is not always obvious how to compare the optical efficiencies of the different types. Even so 'hard numbers' can be found for the transmission and/or reflectance of the displays they often refer to different standards. Some authors use newspaper as a standard for contrast and brightness of the image others use quantities defined by the CIE (Comission Internationale de lEclairage) to calculate values for their displays. We define here a 'three-pixel' colour display illuminated by a white light source of 6500K colour temperature and intensity 1 over the display area as our standard and calculate the colour response and contrast for all 6 display types. Viewing angle and aperture ratio are not included in the calculation. This should give us the 'ideal' values for the optical efficiencies.

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Optical efficiency for different liquid crystal colour displays

Abstract

There are at least 6 fundamental types of liquid crystal displays recorded in the scientific literature. Each type exploits a different physical effect to generate a colour image on the display. It is not always obvious how to compare the optical efficiencies of the different types. Even so ‘hard numbers’ can be found for the transmission and/or reflectance of the displays they often refer to different standards. Some authors use newspaper as a standard for contrast and brightness of the image others use quantities defined by the CIE (Comission Internationale de l’Eclairage) to calculate values for their displays. We define here a ‘three –pixel’ colour display illuminated by a white light source of 6500K colour temperature and intensity 1 over the display area as our standard and calculate the colour response and contrast for all 6 display types. Viewing angle and aperture ratio are not included in the calculation. This should give us the ‘ideal’ values for the optical efficiencies.

1.Introduction

All display manufacturers dream of the perfect display: low cost, high resolution, wide viewing angle, high contrast, full colour, robust, light, bright and minimal power consumption. For most displays the power consumption is directly coupled to the optical efficiency of the display, i.e. how much of the energy fed into the display is transformed into an image visible to the user. Liquid crystal displays are certainly at the lower end of energy consumption. The main energy pumped into the display comes in the form of light, either as a backlight or as light from the environment in the case of a reflective display. The optical efficiency of the display determines now the power of the backlight and therefore the size of the battery used and/or under which lighting condition the display can be used in reflective mode. Comparing the optical efficiencies of different display types can be tricky. There is no international agreement about what should be included or referred to when numbers for transmission or reflectance are compared. Some authors include the eye response; others take the reflectance and the contrast of newspaper as a standard. To avoid all misunderstandings I will define a three-pixel display in an ideal world. I will neglect all viewing angle problems, aperture ratios and the eye response. This should give me the maximal optical efficiency of the display examined. The real gadget can only be worse.

1.1 General set-up

We are looking here at a three-pixel display; that is, our display has a maximum of three different colours, a black and a white state. The display is illuminated by a light source of intensity 1 over the area of the display. The light source is a black body radiator of 6500K colour temperature. It is a good approximation for the daylight of a cloud-covered sky without rain. The daylight of a sunny, cloudless sky is 12000K, but this is hardly used for any colour calculations.

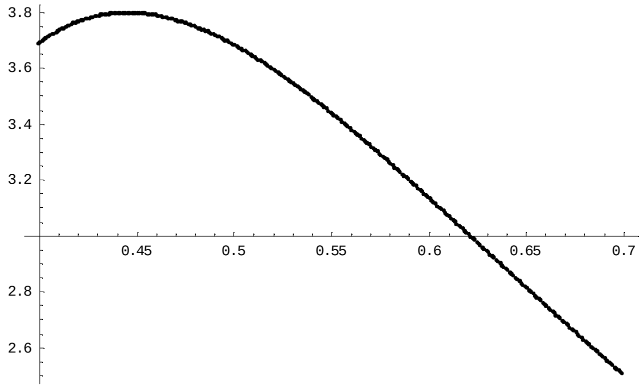

Figure 1: The spectrum of a black body radiator of 6500K is normalised so that the integral over the visible spectrum gives the value 1.The wavelength is in microns.

2. Different LC displays

2.1 The classic LC display

The classic LC display consists of colour filters on top of LC light valves. A LC light valve is liquid crystal material sandwiched between two polarizers or between a polarizer and a special reflector. In a classic LC display the valve switches the light passing through the colour filters on or off, but does not do anything to the colour itself. Traditionally the colour filters are a red, a green and a blue filter in different tiling configurations depending on the display. In the case of the three-pixel display, we have a green, a red and a blue pixel, all of the same size. The colour filters have the following transmission curves:

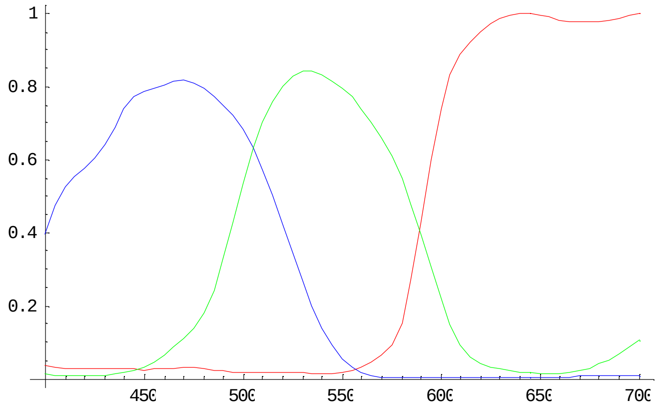

Figure2: Example of transmission curves for red, green, blue colour filters. 1 means all the light incident onto the filter is transmitted. The wavelength is in nm.

In the case of the three-pixel display each filter is only hit by a third times 0.4 of the incoming intensity. Even the best (iodine) polarizers transmit only 40% of the incoming intensity when they are parallel. This leads to a transmission of 4.3% of the incoming intensity through the red pixel, 3.8% through the green pixel, and 4.4% through the blue pixel.
The white state is achieved by opening all light valves. 12.5% of the source intensity is transmitted.

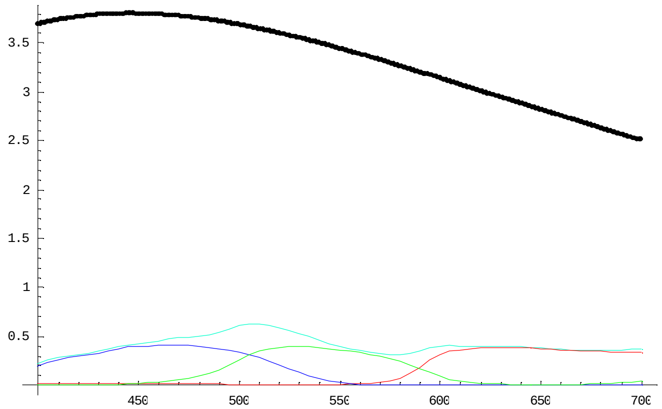

Figure 3:Transmission for the classic LC display. The black curve is the spectrum of the white light source. The red, green, blue curves show the transmission of the red, green, blue pixel, which is 4.3%, 3.8% and 4.4% respectively. The turquoise curve is the white light curve for the three-pixel display. All three pixels are open. The white transmission is 12.5%.

Disappointingly 87.5 % of the source intensity are lost and cannot be recovered.
When all light valves are closed, the display is in the black state. The light valves do not close completely, but well. Very good iodine polarizers transmit about 0.002 to 2% when crossed, depending on the thickness of the polarising layer. Using the definition of contrast from [1], the contrast is defined as
Luminance of the bright state/ Luminance of the dark state.
We get therefore a contrast between 6 (2% transmission) and 6000 (0.002% transmission), which is very good.
The classic LC display has a low optical efficiency, but a good contrast ratio. It is the only display type that has been commercially successful over a longer period of time, even so the production and the power consumption are expensive.

2.2 Electrically controlled birefringence display

2.2.1 Saturated colours

The LC is again sandwiched between two polarizers, but the colour is now generated by the birefringence of the LC itself, i.e. no colour filters are needed. Whereas the colour of a classic LC display is based on absorption, the colour of an electrically controlled birefringence display is based on interference. The formula for the intensity transmitted by a birefringent material in parallel white light with intensity 1 over the display area is [2]:

$$I(d,\alpha,\beta,\gamma)=\cos^2(\alpha-\beta)-\int_{\lambda_1}^{\lambda_2} I(\lambda)\cdot\sin 2\alpha\cdot\sin 2\beta\cdot\sin^2\left(\pi\frac{d}{\lambda}(n_{ef}(\lambda,\gamma)-n_o(\lambda))\right)d\lambda$$

(1).

The spectrum transmitted is

$$\begin{aligned}&spec(\lambda,d,\alpha,\beta,\gamma)=\\&I(\lambda)\cdot\left(\cos^2(\alpha-\beta)-\sin 2\alpha\cdot\sin 2\beta\cdot\sin^2\left(\pi\frac{d}{\lambda}(n_{ef}(\lambda,\gamma)-n_o(\lambda))\right)\right)\end{aligned}$$

(2)

where *I(l)* is the spectrum incident onto the display, d is the thickness of the birefringent material, α the angle of the direction of transmission of the polarizer with the optic axis of the material, β the angle of the direction of transmission of the analyser with the optic axis and γ the angle which the wave normal s makes with the optic axis.

$$n_{ef}(l, g) = \sqrt{\frac{1}{\frac{\cos^2(g)}{n_o^2(l)} + \frac{\sin^2(g)}{n_e^2(l)}}} \tag{3}$$

is the effective refractive index for the extraordinary channel. If the wave normal of the light incident onto the liquid crystal is not parallel to the optic axis, the value of the extraordinary refractive index will change continuously between the values no and ne the as a function of the deviation of the wave normal from the direction of the optic axis. This allows changing the birefringence of the liquid crystal by changing the orientation of its molecules. It is well known that when the birefringent material is too thin or too thick the colours are murky (crossed polarizers) or pastel (parallel) polarizers. But there is a region in-between where the birefringent colours are vivid and saturated. In [2] a table is published that describes the interference colours (really describes the colours by giving colour names) as a function of the optical path difference generated by the difference of the refractive indices. This table neglects that the refractive indices are functions of the wavelength as well, but it is nevertheless a rough guide where the saturated colour region is.

Here are three blues from this table. The first one is a grey-blue between crossed polarizers for an optical path difference 2l = 0.158 µm . The value of 0.158 µm translates into a cell thickness of about 1.2 µm for a cell filled with ZLI 2293 and the s-vector perpendicular to the optic axis.

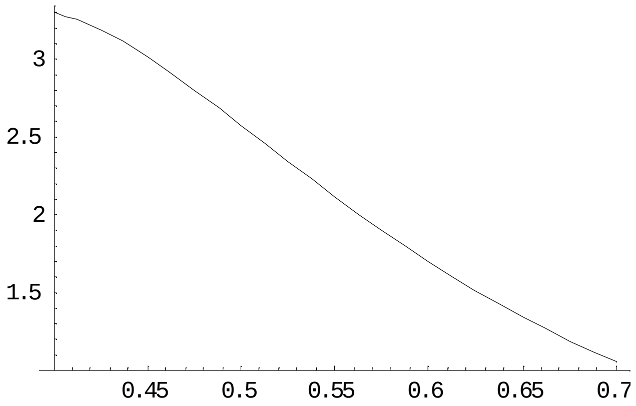

Figure 4: Transmitted intensity through a LC layer between crossed polarizers. The ZLI2293 filled cell is about 1.2 µm thick and the s-vector of the light is perpendicular to the optic axis. It is a murky blue.

Even so the transmitted spectrum has a maximum in the blue the colour appears murky because all colours in the visible range contribute with considerable intensities.

The second one is a saturated indigo for a cell of about 4.3 µm (2l = 0.589 µm).

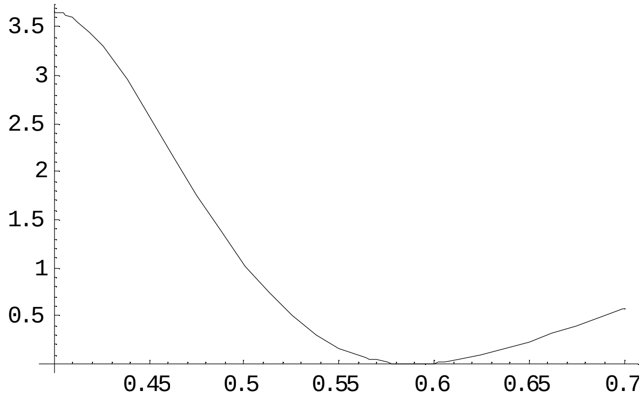

Figure 5: Transmitted intensity through a LC layer between crossed polarizers. The ZLI2293 filled cell is about 4.3 μm thick and the s-vector of the light is perpendicular to the optic axis. It is brilliant blue.

The spectrum has 0 intensity minimum in the yellow region. The contribution from the red-end of the spectrum is less then 10% of the overall-intensity in the blue/green region.
The third blue is a pale blue, but now for a cell of about 12 μm thickness (2l = 1.682 μm).

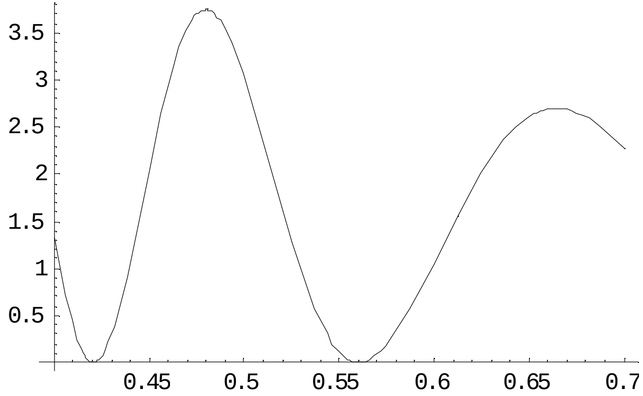

Figure 6: Transmitted intensity through a LC layer between crossed polarizers. The ZLI2293 filled cell is about 12 μm thick and the s-vector of the light is perpendicular to the optic axis. It is a pale blue.

The spectrum has a very different shape compared to that of the murky blue. We have got here two clear 0 intensity minima, but the contributions from the blue/green region and the orange/red region are almost equal.
The thickness of the liquid crystal layer has to be chosen carefully. Otherwise the colours loose saturation and the display is not suitable for real colour presentation.

2.2.2 A liquid crystal layer between crossed polarizers

The LC is between crossed polarizers. The dark state is achieved by aligning the optic axis of the LC parallel to the light direction. The white state is achieved by opening all three colour pixels and 'reconstructing' a white spectrum (same method as in the classic LC display). Tilting the LC molecules generates birefringence and therefore interference colours. I don't want to go into technical details what sort of liquid crystals would be most suitable, but I would like to use ZLI 2293 as an example since I have got the dispersion data for it [3]. The formulae for the refractive indices are:

$$n_o = 1.4797 + \frac{6745 \cdot 10^{-6}}{l^2} \qquad (4)$$

$$n_e = 1.5934 + \frac{13407 \cdot 10^{-6}}{l^2} \qquad (5)$$

The wavelength is again in µm.

To generate the three colours red, green, blue, we start with a ZLI 2293 filled cell of 5.7 µm thickness.

For green the optic axis of the LC is perpendicular to the direction of the light and at 45° to the first polarizer. The transmitted spectrum is:

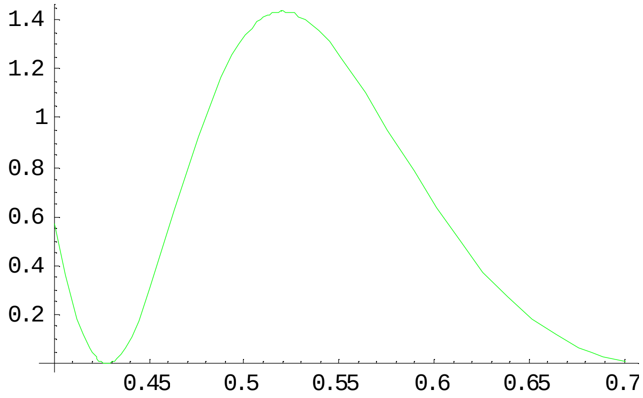

Figure 7: Green transmitted through a LC layer between crossed polarizers. The ZLI2293 filled cell is about 5.7 µm thick and the s-vector of the light is perpendicular to the optic axis orientated at 45° to the first polarizer.

Since we have no colour filters, we can switch all three pixels into the green state and we get 19% of the white light intensity as green light. That is 5 times more intensity than for a green classic display (where the red and the blue filter have to be switched off).

For blue the LC is now tilted 65° away from the light direction.

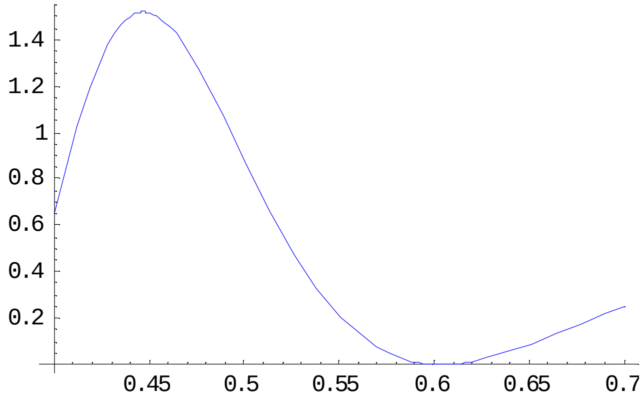

Figure 8: Blue transmitted through a LC layer between crossed polarizers. The ZLI2293 filled cell is about 5.7 µm thick and the s-vector of the light is at 65° to the optic axis orientated at 45° to the first polarizer.

The intensity of the blue light is 16% of that of the white light. And again that is 3.7 times more than in the classic case.

A good red is a little bit tricky. We can achieve a cherry rose by tilting the LC 52° away from the light direction.

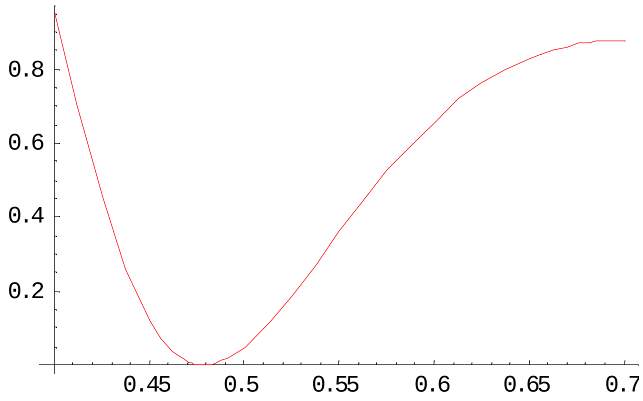

Figure 9: Red transmitted through a LC layer between crossed polarizers. The ZLI2293 filled cell is about 5.7 µm thick and the s-vector of the light is at 52° to the optic axis orientated at 45° to the first polarizer.

In the red state the intensity is lowest with 14% of the light incident on the LC, but it is still 3.3 times more than in the classic case. In the case of crossed polarizers the colour for which the optic axis of the LC is perpendicular to the light direction will have the highest intensity. To generate white we will switch one pixel into the blue state, one into the red state and one into the green state.

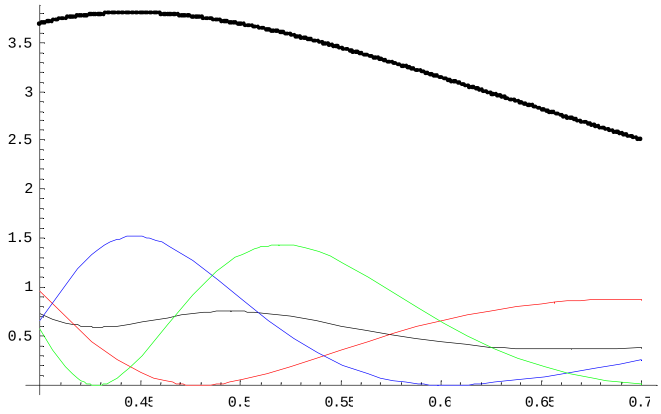

Figure 10: Transmitted intensity through a LC layer between crossed polarizers. The upper curve is the spectrum of the white light source. The lower black curve is the white light transmission (16%) of the display, i.e. the three pixels are switched into three different colours. The red, green, blue curves show the transmitted intensities when all three pixels are switched into the same colour state. We have 14%, 19% and 16% transmission respectively.

The intensity of the so generated white is 16% of the white light intensity of the light source that is just 1.3 times more than for the classic LC display.

Is the optic axis in the direction of the light, the contrast is again a function of the quality of the polarizers. For transmission of the crossed polarizers between 0.002% and 2% we get contrast ratios between 8000 and 8 for the white state.

The white light transmission of this kind of display is not much higher than that of the classic LC display. But the transmission of a single colour is about 3 times higher compared to the classic case, simply because all the three pixels can be switched into the same state, and therefore same colour. The contrast is again only a function of the extinction ratio of the crossed poalrizers and therefore very high.

2.2.3 A liquid crystal layer between parallel polarizers

The LC layer is now between parallel polarizers. The white state is achieved by aligning the optic axis of the LC parallel to the light direction. The material appears isotropic and the source intensity times 0.4 is transmitted. The overall intensity of the light source is only weakened by the absorption of the parallel polarizers. Tilting the LC and therefore modifying ne generates the colours. The dark state is a problem. The polarizers are not crossed anymore. An untwisted liquid crystal layer cannot rotate the polarisation of the light by 90°. The state of minimal light transmission will therefore transmit substantially more light then in the case of crossed polarizers.

We start again with green. The optic axis is again perpendicular to the direction of the light, but the cell has to be thicker. It is now 7.6 μm.

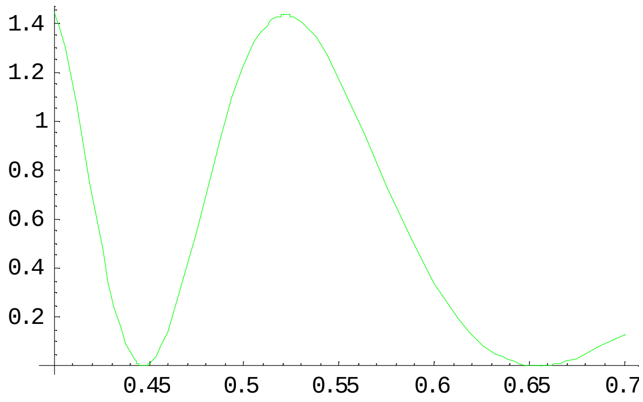

Figure 11: Bluish green transmitted through a LC layer between parallel polarizers. The ZLI2293 filled cell is about 7.6 μm thick and the s-vector of the light is at 90° to the optic axis orientated at 45° to the first polarizer.

We switch again all three pixels into the green state and get 17% of the light incident transmitted through the display, that is about 4 times as much as in the classic configuration. For the blue the optic axis of the LC is tilted 70° away from the direction of the light and the transmitted intensity is 16% of the source intensity.

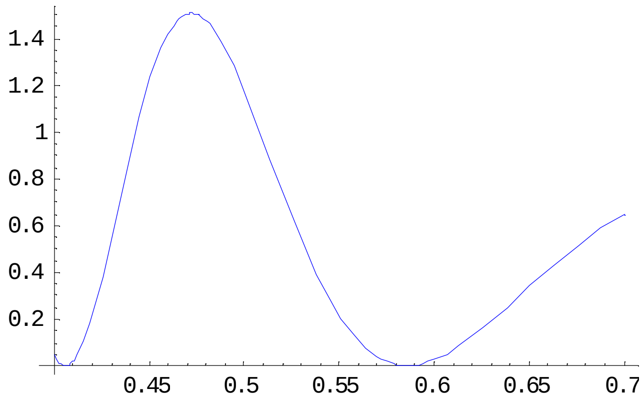

Figure 12: Brilliant blue transmitted through a LC layer between parallel polarizers. The ZLI2293 filled cell is about 7.6 µm thick and the s-vector of the light is at 70° to the optic axis orientated at 45° to the first polarizer.

The red is this time the brightest state with 23% transmitted intensity, that is almost 6 times as much as in the colour filter configuration. The optic axis is at 55°.

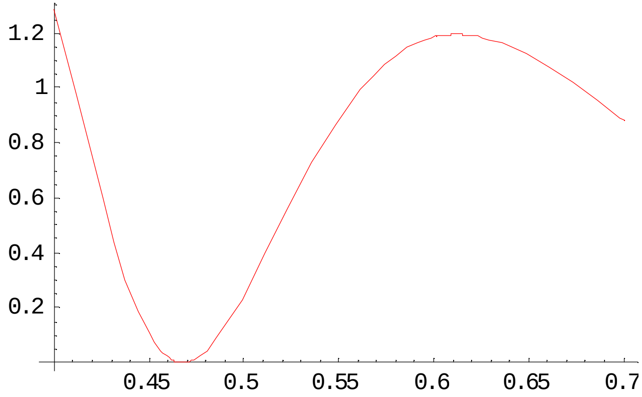

Figure 13: Salmon pink transmitted through a LC layer between parallel polarizers. The ZLI2293 filled cell is about 7.6 µm thick and the s-vector of the light is at 55° to the optic axis orientated at 45° to the first polarizer.

The darkest state, a blue, transmits 15% of the incoming light.

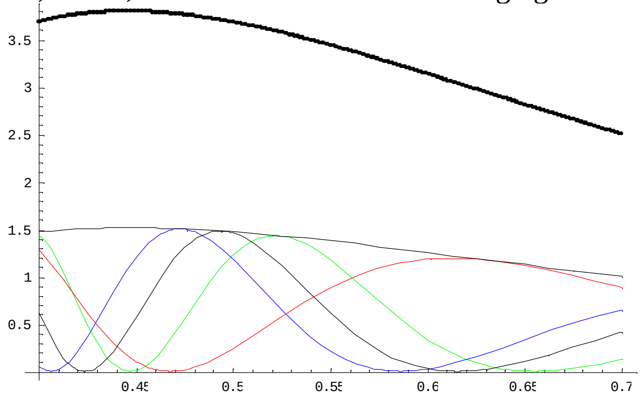

Figure 14: Transmitted intensity through a LC layer between parallel polarizers. The upper curve is the spectrum of the white light source. The lower black curve is the white light transmission of the display, i.e. 0.4 times the white light spectrum. The red, green, blue curves show the transmitted intensities when all three pixels are switched into the same colour state. We have 23%, 17% and 16% transmission respectively. And the black curve between the blue and the green curve is the curve of minimal transmission (15%).

The curve of minimal transmission lies between the green and the blue curve. The observer could even perceive this blue brighter than the more intensive blue since it is shifted more to the green. The transmission of the white state is with 40% more than double of the white transmission of a LC between crossed polarizers. But from fig 14 it is clear that the contrast is lousy. With 2.7 it is certainly on the flat side.

2.3 Dye Phase Change Display

This kind of display does not use any polarizers. Instead a strongly dichroic dye is immersed in the liquid crystal. The dye molecule couples to the LC so that it follows the orientation of the LC molecules. It is therefore possible to switch the dye from its non-absorbing mode/orientation into its absorbing mode/orientation. One prototype is a triple layer display

([4],[5],[6],[7]). Three layers with three different dyes are stacked on top of each other. When all layers are in the non-absorbing state the stack is transparent. This is the white state. All layers switched coloured results in a black state.

The colour generation is now rather subtractive than additive. We have therefore magenta, cyan and yellow instead of red, green, blue. The performance of the display depends very much on the choice of dye. Since I have not yet found any transmission curves for the layers used in prototypes, I will compare the optical efficiency of layers simulated by Wratten filters with the one simulated by minus-red, minus-green, minus-blue filters. The Wratten filters consist of dye molecules suspended in gelatine and then sandwiched between glass plates. They should come close to the performance of the layers in the dye phase change display, but of course they cannot be switched.

For yellow I have chosen Wratten#16, for magenta Wratten#32, and for cyan Wratten#38 [8]. Each layer can be switched into a transparent state or a coloured state. The white state, i.e. all light is transmitted, transmits therefore intensity 1 = 100%.

The cyan state transmits 47%, the magenta state 41% and the yellow state 44% The dark state transmits only 1.6% of the intensity incident onto the display. Remember no polarizers are used! The dark state is achieved by switching all layers into the coloured states. We have here a very good contrast of 62.5

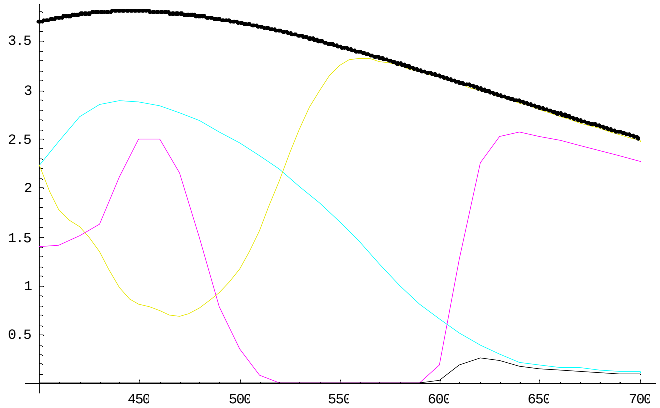

Figure 15: Transmitted intensity through dye phase change display. The upper curve is the spectrum of the white light source and the transmission curve for the white state = 100%. The lower black curve is the transmission of the black state, only 1.6% of the incoming light. The cyan, magenta, yellow curves are the transmission curves for the cyan, magenta, yellow layers. The cyan layer transmits 47%, the magenta layer 41% and the yellow layer 44%.

But [5],[6] report a contrast ratio of only 5. They must use different dyes, perhaps more of the minus-red, minus-green, minus-blue form.

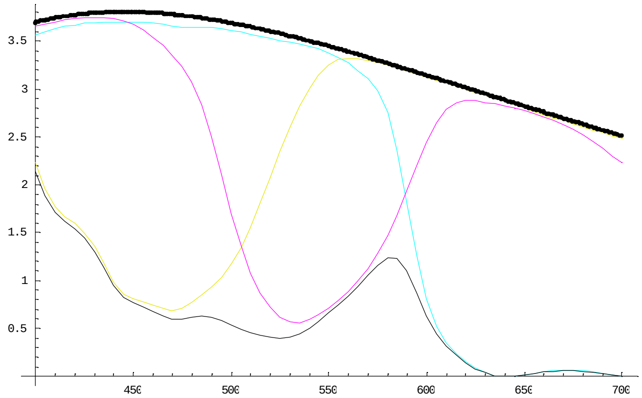

Figure 16: Transmitted intensity through dye phase change display. The upper curve is the spectrum of the white light source and the transmission curve for the white state = 100%. The lower black curve is the transmission of the black state, now 18% of the incoming light. The cyan, magenta, yellow curves are the transmission curves for the cyan, magenta, yellow layers. The cyan layer transmits 69%, the magenta layer 73% and the yellow layer 68%.

The transmission for each colour goes up by about 50%. Cyan transmits now 69% of the incoming intensity, yellow 68% and magenta 73%. But the black state becomes much brighter. Instead of 1.6% it transmits now 18% of the source intensity. The contrast goes down to 5, which is now the literature value.

The display can not only be driven in ‘printing mode’ using cyan, yellow, magenta as primary colours, but also in ‘display mode’ with red, green, blue as primary colours. The light transmission for a single colour decreases, but is still not too bad. For the Wratten filters we get for red 21% transmission, green 8% transmission and blue 14% transmission. For the minus filters the transmission is higher and more homogeneous. The red transmission is 47%, green transmission 37% and the blue one 44%. Black and white stay the same in both cases. Therefore the contrast remains unchanged: 63 for the Wratten filters and 5 for the minus filters.

2.4 Polymer dispersed Liquid Crystal Display

In a polymer dispersed liquid crystal display ([9],[10]) or a polymer stabilised cholesteric texture a liquid crystal ([11]) is dispersed in a polymer matrix. This can be achieved by two methods [9]. In the emulsion method, the liquid crystal and a polymer solution are physically mixed to form a stable emulsion with liquid crystal micro-droplets whose size is well controlled. The emulsion is coated in one of the panel substrate, which is subsequently laminated with the other to complete a panel. In the phase separation method micro-droplets are formed in a homogeneous mixture of liquid crystal and monomers by polymerisation process typically induced by UV light. The material can be switched into two states: one that transmits almost all the light and one that scatters very strongly and transmits therefore almost nothing. In the case of nematic dispersion in polymers the polymer has more or less the same refractive index as the LC. The transparent state is achieved by ‘aligning’ the optic axes of the LC droplets with the polymer. For the polymer stabilised cholesteric texture the transparent state can be achieved by two methods [11]. If the polymer stabilises the focal conic texture (see 2.5), the cell appears opaque in the field free state and can be switched into the transparent homeotropic state with an electrical field. If the planar state is stabilised and the helical pitch is chosen to in the IR the cell appears transparent in the field off state and becomes scattering when switched into the focal conic texture (reverse mode operation). 90% of the incoming light is transmitted when the cell is in the clear state and about 3% when the cell is in the scattering state. In general this type of LC light valve is combined with red, green, blue filters. It has a higher brightness compared to the classic LC since there is no need for polarizers.

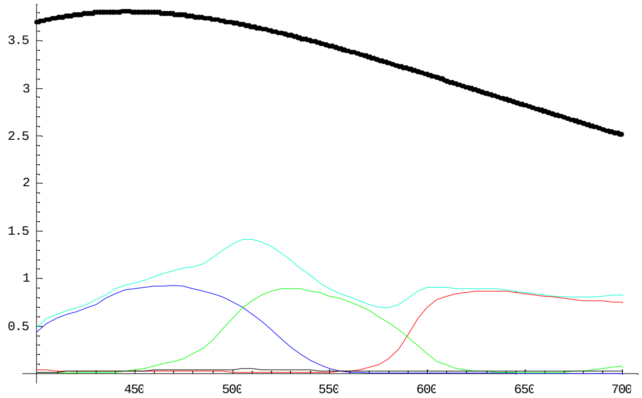

Figure 17: Transmitted intensity through a polymer dispersed liquid crystal display. The upper curve is the spectrum of the white light source. All three pixels open is the white state (turquoise). 28% is transmitted. The curve for the black state is hardly visible. Red, green, blue go up to 9.6%, 8.5% and 10%.

The transmission of the white state goes up from 12.5% to 28%, of the red pixel from 4.3% to 9.6%, of the green pixel from 3.8% to 8.5% and of the blue pixel from 4.4% to 9.9%. The black state transmits about 1% of the incoming state. The contrast ratio is therefore about 28.

2.5 Reflective Cholesteric Liquid Crystal Display

Cholesteric liquid crystals have two features ([12]) that make this kind of display work. 1. The spiral structure of the liquid crystal acts when illuminated parallel to the axis of the spiral like a Bragg reflector. It exhibits a band selective reflection centred at the wavelength

$$l_0 = pn_{eff} = \frac{p(n_o + n_e)}{2} \tag{6}$$

where p is the pitch and ne and no are the extraordinary and ordinary refractive indices of the cholesteric liquid crystal . The width $\Delta\, l$ of the band follows from

$$\Delta\, l = \frac{l_0 \Delta n}{n_{eff}} \tag{7}$$

with $\Delta n = (n_e - n_o)$. Within the selective-reflection band, the circularly polarised component of incident light, which exhibits the same twisting sense as the cholesteric helix, is totally reflected, whereas the opposite circular polarisation is transmitted without attenuation. The typical band has a bandwidth of about 100nm. Outside the selective reflection band the filter is fully transmissive and non-polarising.

2. Bistability: There are four known states in cholesteric liquid crystal systems. 1. The equilibrium planar state. It is formed by helices with pitch p. The helical axes are perpendicular to the substrate and generate colour due to the Bragg reflection just described. 2. The focal conic state. In this state the helical axes are parallel to the substrate. The focal

conic state is weakly forward scattering. If the rear substrate is painted black, this state appears dark. 3. The homeotropic state. It is only found when a field is applied. In this state the liquid crystal is homeotropically aligned. 4. The transient planar state. This state has helices aligned perpendicular to the substrate, but with a different pitch. It shows Bragg reflection. Only the planar and focal conic state are stable at zero field. They are exploited for the reflective display.

a) Performance of the reflective display

Kent Displays built at least a prototype of the reflective display ([13]). On a black absorber a 'red', a 'green' and a 'blue' layer are stacked. When all layers are in the focal conic state the pixel is black and reflects about 3-4% of the incoming light. The chirality of the layers is alternating to recycle the overlapping parts of the spectra of the layers, i.e. the reflection bands of the blue and green overlap but because of the opposite chirality no green light is lost even so the green cell is underneath the blue one. The same holds true for the bottom red cell with a band overlapping the upper green cell. The following plot shows the reflected intensity for such a stack assuming that the reflected spectrum of each layer has a Gaussian distribution around the central wavelength and a bandwidth of up to 100nm.

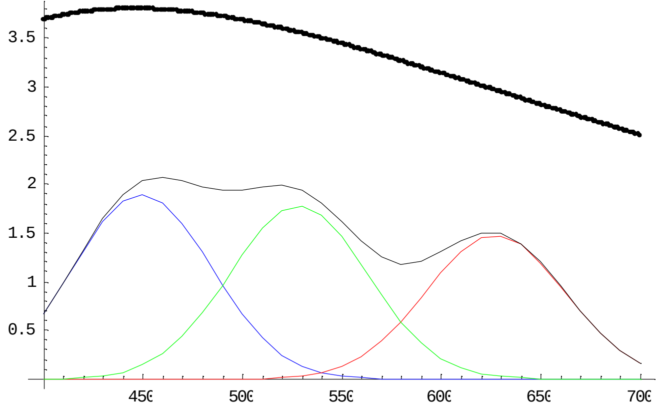

Figure 18: Transmitted intensity through a reflective cholesteric liquid crystal display. The upper curve is the spectrum of the white light source. All three pixels reflecting is the white state (lower black curve). 44% is transmitted. The red layer reflects 12.7%, the green 15.5% and the blue 15%.

Since only the light of the correct handedness is reflected the reflectance of each layer is less than hoped for. The red layer reflects 12.7% instead of 25.4%, the green layer 15.5% instead of 31% and the blue layer 15% instead of 30%. The white state reflects about 43% of the incoming light. With 3-4% coming back from the black absorber we have a contrast of 11-14.

b) Performance of the transmissive display

If we use the same display in transmissive mode we get the colours cyan, magenta and yellow. The white state, i.e. all layers in the focal conic state, transmits about 96%. The colours are very bright (between 84 and 87% of the incoming intensity), but not very saturated, since only half of the intensity of a colour band is subtracted from the incoming intensity spectrum.

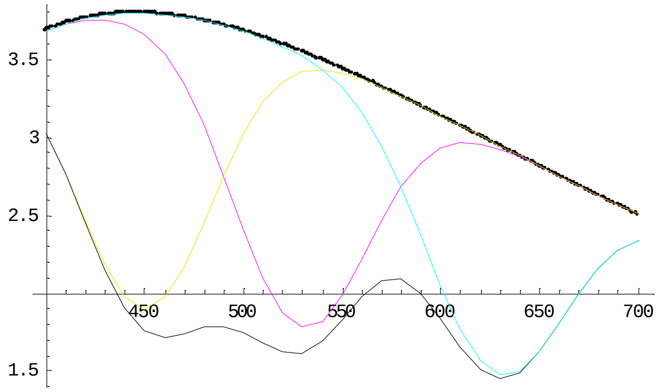

Figure 18: Transmitted intensity through a transmissive cholesteric liquid crystal display. Magenta transmits 84.5%, yellow 85% and cyan 87%. The colours are very pastel. And the black very grey with a transmission of 56%.

And the black is lousy. It is (1- the white intensity of the reflective display), i.e. about 56% of the incoming intensity. That makes a contrast ratio of 96/56 of about 2.

2.6 Holographically fabricated polymer-dispersed liquid crystal display (HPDLC display)

HPDLC has a periodic structure that consists of polymer and nematic-liquid-crystal droplet layers. The refractive index of the polymer is more or less equal to the refractive index of the optic axis of the LC. But because the LC in the droplets is randomly aligned, the refractive index of the polymer does not match that of the droplets. The resulting periodic modulation of the refractive index reflects light of a specific wavelength according to the Bragg condition. When an electric field is applied, the LC rotates in the droplets and its refractive index matches then the one of the polymer. The HPLDLC becomes transparent. The periodic arrangement of the droplets is achieved by exposing the LC/polymer mixture to a two beam interference pattern at the wavelength, which should be reflected. A phase separation takes place and layers of LC droplets are formed. The colour reflected by such a device has a quite sharp peak and is therefore very saturated. The bandwidth of the reflected band is about 20nm ([14],[15]). The device is not polarising, i.e. all the light within the reflection band is reflected.

The full-colour HPDLC display has the same stack structure as the cholesteric liquid crystal display, but its spectral output looks different.

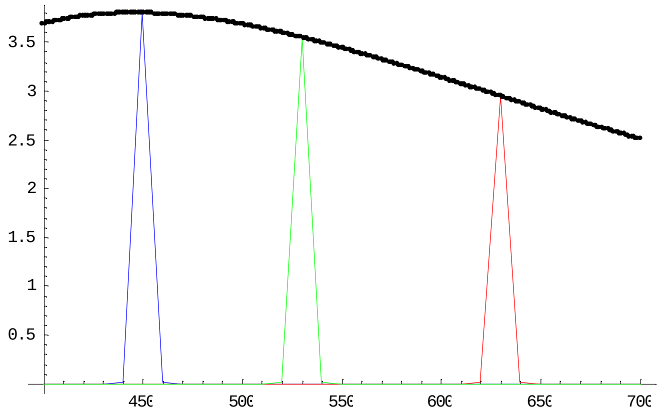

Figure 19: Reflected intensity of a HPDLC display. The blue filter reflects 3.8% of the incoming intensity, the green filter 3.6% and the red filter 3%. The white transmission is the sum of the three peaks = 10.4%.

The layers of the HPDLC are narrow-band filters. They reflect saturated colours, but not high intensities. The blue band is only 3.8% of the incoming intensity, the green band 3.6% and the red one 3%. That gives for the white state a reflectance of 10.4% of the incoming intensity. This is even less than the classic LC display and contradicts the estimates by Crawford and Silverstein of 34% [15]. With an estimated reflectance of 3% in the dark state we get a contrast of about 3.

3. Discussion

Displays using polarisation effects cannot transmit or reflect more than 50% of the light incident on the display. In reality this maximal percentage slides down to 35% - 40% because of the absorption bands of foil polarizers in the visible spectrum. The most promising candidate of this group is the electrically controlled birefringence display. One can choose between two versions: the parallel polarizer type with high white transmission, but low contrast or the crossed polarizer type with a white transmission of only 16%, but a very high contrast. In the group of the non-polarising displays the ones that stack the colour filters are the most promising. Not only that they transmit high single colour intensities, but they also promise to be suitable for high resolution displays. Looking at table 1 the clear winner is the dye phase change display. It combines a high brightness with a dark black, and therefore generates a good contrast. The single colour transmissions are very much on the high side. And it can be driven in two modes: the printing mode with cyan, yellow, magenta as primary colours and the display mode with red, green, blue as primary colours. The main problem with this kind of display is the robustness of the dyes. Most dyes are sensitive to UV. This can be even a problem with colour filters.

The consensus in the literature is that the classic LC display, i.e. the LC light valve with colour filters, will disappear as soon as at least one of the non-polarizer techniques will be robuster.

Table 1: Comparison of the different display types.

Classic LCD: Classic liquid crystal display; ECBT p.p.: Electrically controlled birefringence display, parallel polarizers; ECBT c.p.: Electrically controlled birefringence display, crossed polarizers; DPCD CYM: Dye Phase Change Display, cyan, yellow, magenta; DPCD RGB: Dye Phase Change Display, red, green, blue; PDLCD: Polymer dispersed liquid crystal display; RCKCD refl.: Reflective cholesteric liquid crystal display, reflective; RCLCD trans.: Reflective cholesteric liquid crystal display, in transmission mode; HFPDLCD: Holographically fabricated polymer-dispersed liquid crystal display.

	Classic LCD	ECBT p.p.	ECBT c.p.	DPCD CYM	DPCD RGB	PDLCD	RCLCD Refl.	RCLCD Trans.	HFPD LCD
White	12.5 %	40%	16%	100%	100%	28%	43 %	96%	10.4%
Black	0.002-2%	15%	0.002-2%	1.6-18%	1-18%	1%	3-4%	56%	3%
Contrast	6000-6	2.7	8000-8	62.5-4	100-4	10	11	2	3
Red	4.3%	23%	14%	/	21-47%	9.6%	12.7%	/	3%
Green	3.8%	17%	19%	/	8-37%	8.5%	15.5%	/	3.6%
Blue	4.4%	16%	16%	/	14-44%	9.9%	15%	/	3.8%
Cyan	/	/	/	47-69%	/	/	/	87%	/
Magenta	/	/	/	41-73%	/	/	/	84.5%	/
yellow	/	/	/	44-68%	/	/	/	85%	/

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