Chromatic parameter space representation of LCD operating modes

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Abstract: A chromatic parameter space (CPS) representation is proposed to represent the operation of LCDs. Both chrominance and luminance are visualized in the CPS diagrams. All the usual display modes, both transmissive and reflective, such as TN, ECB, OMI, STN, and SBE are shown clearly on the diagrams. Two designs with the help of CPS are proposed and demonstrated: multicolor STN and a novel fully-compensated reflective STN with high brightness and almost no chromatic dispersion

Introduction

Optical modeling is very important in designing and optimizing liquid crystal displays (LCDs) [1~3]. In previous work [4], we proposed a new systematic technique called parameter space (PS) representation of all nematic LCDs. This PS approach is very helpful in understanding the physical operation of various LCD modes and their relationships. With the help of the PS, we also analyzed the various different reflective LCD designs and developed several new reflective LCD operating modes[5~7].

However, in our previous work, the PS is calculated only for a single wavelength, normally 550nm. Thus it does not show the appearance of the LCD under white light illumination. Even though the monochromatic PS can provide an idea of the chromatic dispersion behavior of the various LCD modes, it is still desirable to devise a scheme where the chromaticity of the display can be shown more clearly. It is particularly so for LCDs with considerable chromatic dispersion, such as STN displays.

In this paper, a chromatic parameter space (CPS) representation is proposed and demonstrated. Both chrominance and luminance are visualized in the same diagram with the help of color representation. The real appearance of the LCDs in the static state (voltage-off or nonselect state) can be shown in the CPS diagram, both in terms of brightness and color.

Using this new CPS, we analyzed the chromatic dispersion of various display modes, both transmissive and reflective. Furthermore, in this paper, we shall show two examples of the application of this CPS in designing new LCDs with good performance: (1) Multicolor STN (2) Fully-compensated reflective STN with high brightness and almost no chromatic dispersion. It is interesting to note that in the first case, we make use of chromatic dispersion to achieve multicolor display. In the second case, we do our best to eliminate chromatic dispersion. These two cases provide a good demonstration of how CPS can be used for LCD design and novel device development.

Chromatic parameter space

The reflectance or transmittance of an LCD is determined by four variables: input polarizer angle α, output polarizer angle γ, twist angle ϕ, and retardation value $d\Delta n$. Any pair of these variables can be used to generate a contour map which is called the PS diagram[4]. The calculation assumes a fixed wavelength λ. The idea of the CPS is to repeat the PS calculation for all λ in the visual range (380nm ~ 780nm), and obtain the luminance and chrominance of the output assuming a standard white light input source.

In this paper, CIE D65 is used as the incident light. From the output spectrum, we can obtain the CIE 1931 XYZ values. The XYZ color coordinate is transformed to the standard color space: sRGB, which is proposed by Hewlett-Packard and Microsoft [8]. The sRGB tristimulus values can be computed using the following relationship:

$$\begin{bmatrix} Rs \\ Gs \\ Bs \end{bmatrix} = \begin{bmatrix} 3.2410 & -1.5374 & -0.4986 \\ -0.9692 & 1.8760 & 0.0416 \\ 0.0556 & -0.2040 & 0.3583 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$

The sRGB tristimulus values are next transformed to nonlinear digital code RGB values which can be directly displayed on CRT terminals. The color and the relative brightness of the calculated parameter space on the CRT display are therefore nearly the same as that of the real LCDs. This will be the desired chromatic parameter space. The contour map of luminance can be added to the color chrominance map to obtain the complete CPS.

The CPS is obviously more time-consuming to generate than the monochromatic PS. However it is still manageable with the development of some fast algorithms.

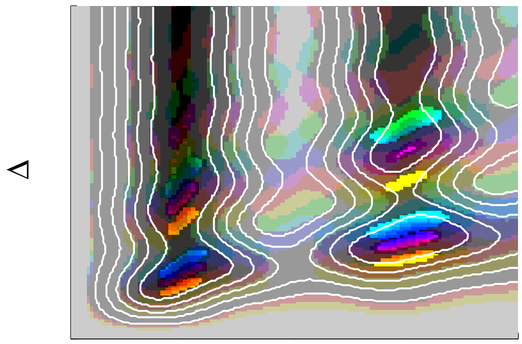

Fig.1 CPS diagram for transimissive LCD with α=0° and γ=0°

CPS for transmissive LCDs

In transmissive LCDs, there are two typical arrangements for the polarizers: α=0° and α=45°. Fig. 1 is a CPS diagram with α=0° and γ=0°. Each contour line shows a 0.2 increase in luminance. In Fig.1, 90° TN corresponds to the vertical line of ϕ=90°, point 'T' is identical to the typical TN operating mode. Point 'B' with ϕ=270° is similar to the SBE mode with a different polarizer arrangement (for SBE, α=-32.5° and γ=32.5°). It will be called the SBE-like mode. Point 'M' is very similar to the OMI mode, nearly white-black display can be obtained. However, the contour map of luminance shows that its brightness is only 0.45, which is expected.

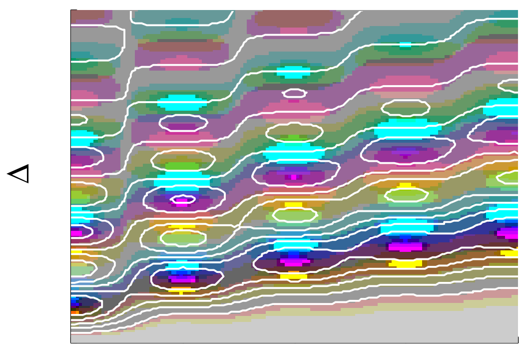

Fig.2 CPS diagram for transmissive LCD with α=45° and γ=45°

Fig. 2 shows the CPS diagram of transmissive LCDs with α=45° and γ=α. The ϕ=0° line in the diagram is exactly the ECB mode. The ϕ=180° line is very similar to 180° STN mode. Point 'S' is just the typical yellow-mode of 180° STN. Point 'B' with ϕ=270° is also a SBE-like mode.

Comparing Fig. 1 and Fig. 2 , it is seen clearly that Fig. 2 shows a much larger chromatic dispersion than Fig. 1. The reason is simply that for α=0°, there is waveguiding effect for large dΔn[1]. When α=45°, the displays are mainly based on the interference effect. Unlike α=0°, the chromatic dispersion for α=45° increases with increasing dΔn. There is no dark state possible.

Design of multicolor STN

A multicolor STN display is one that will show different colors as the voltage is changed. As seen in Fig. 1 and 2, the chromatic dispersion can be used to achieve multicolor displays. However, it should be noted that if chromatic dispersion is too large, the different colors will be mixed and no fresh color appears. So, the degree of chromatic dispersion must be selected properly.

As we have pointed out [4], the CPS is only valid for V=0 or V=nonselect voltage. So it is impossible to predict the color of the LCD as the voltage is increased. However, an idea of the dynamic behavior of the LCDs can be obtained from the ϕ-dΔn diagram. When the applied voltage is increased, the effect should be similar to a decrease in dΔn. Therefore the color of the LCDs can be seen from the ϕ-dΔn diagram.

For example, if the multicolor STN has a static operating condition corresponding to point 'A' in Fig. 2, then it is nearly green at V=0. If the voltage is increased, we predict that the color will change in the sequence of: green-white-magenta-green-blue-yellow-white.

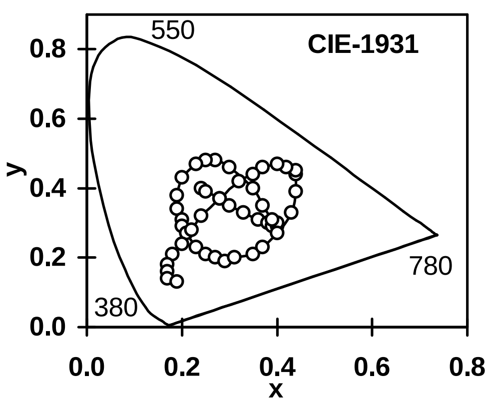

Fig.3 Experimental results of a multicolor STN cell in the CIE 1931 chromaticity diagram.

After the operating mode is selected, numerical simulation is performed to examine the dynamic performance when a voltage is applied. In calculating the color as a function of voltage, first the 1D Euler-Lagrange equations are solved to give the director angles $\phi(z)$ and $\theta(z)$. Then the transmission is calculated by the extend Jones matrix method. The transmission spectrum is then used to calculate the color coordinates.

Fig.3 shows the experimental results of the cell with the parameters indicated by point “A” in Fig.2. The color of the LCD as a function of the applied voltage is plotted in a CIE 1931 chromaticity diagram. The voltage is varied from 1.1V to 2.0V. The color starts out as pure blue, then changes to white, red, blue green etc. The color sequence generally follows the prediction from Fig. 2. It indicates that Fig. 2 can be used to design color displays for any combination of colors.

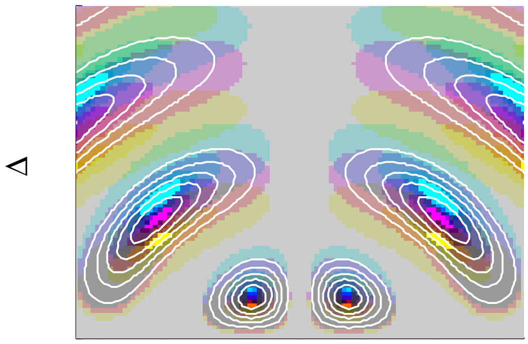

Fig. 4 CPS diagram of reflective LCDs for α=0°

CPS diagram for reflective LCDs

In reflective LCDs, the back polarizer is eliminated and the rear mirror can be placed either inside or outside the LC cell. For such reflective displays, there are only three parameters: α, ϕ ,and $d\Delta n$. Fig. 4 is a CPS diagram of reflective LCDs at α=0°. A single sheet polarizer is assumed. (The other possibility is using a PBS as the polarizer). In Fig. 4, the reflectance minima which are indicated by the dark “wells” are called the TN-ECB modes [9]. As we have shown in previous papers[10], when α is increased, the TN-ECB modes move towards the center of the diagram, finally the ‘+’ and ‘-’ TN-ECB modes interleaves each other at α=45°.

All possible display modes can be presented by a series of CPS diagrams for α varying from 0° to 45°. Normally black (NB) reflective displays, like MTN, SCTN, must select TN-ECB modes as their static states. Fig. 4 shows that high order TN-ECB modes have much larger color dispersion, so normally only the first order TN-ECB modes are useful for making B/W displays. For normally white (NW) displays, like HFE, RTN and RSTN, the operating mode can be selected over a wider space. The point ‘H’ in Fig. 4 indicates the operating mode of HFE.

Fully-compensated reflective LCD

In our previous works, several new reflective displays have been developed, such as the RTN [6] and RSTN [7]. In reference 5, we also proposed a colorless display with a retardation film placed between the LC cell and the reflector. A wide band retardation film is needed here, the phase retardation has to be constant for the entire visible range. This kind of film has been recently developed and is available in the market.

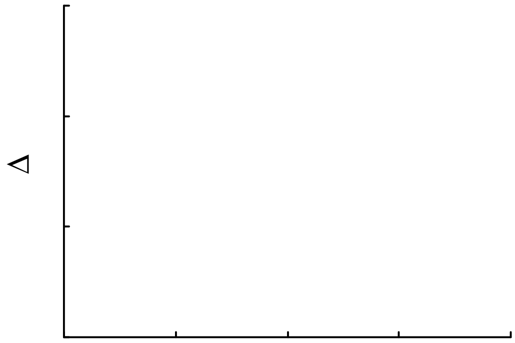

Fig. 5 CPS diagram of a reflective display with a $\lambda/4$ retardation film, α=0°

We shall use the CPR approach to reanalyze such displays. Fig. 5 shows the CPS diagram of a reflective display with a $\lambda/4$ retardation film. α=0° and the angle of optical axis of the film is 45°. In Fig. 5, the region indicated by ‘W’ is a good candidate for the reflective display. The parameters of this cell therefore are: ϕ=180°, $d\Delta n$=0.52µm, and α=0°.

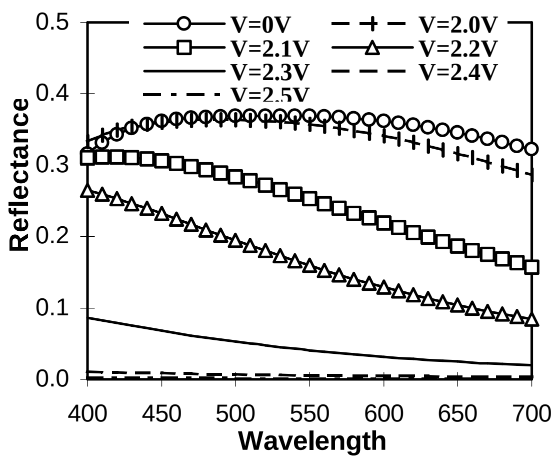

Fig.6 Simulation results of the output spectra of the fully compensated reflective STN cell under different voltages.

After the parameters are selected, numerical simulation is performed to study the dynamic behavior. Fig. 6 shows the spectra of the reflected light under different applied voltages. It is clearly shown that a true white-black display with high brightness and almost no chromatic dispersion is obtained. A polarizer efficiency of 50% was assumed in that calculation.

The mechanism of this display is totally different from conventional film compensated STN. It is actually similar to the double-layer STN. Furthermore, the self compensation effect is active for both the select and nonselect voltages. So we call it a fully-compensated reflective LCD. The drawback of this display is that a retardation film is placed at the back of the cell, thus limiting its usefulness.

Fig.7 shows the experimental results of the fully compensated reflective STN cell. A normal $\lambda/4$ retardation film with large dispersion was used in this measurement. The dash line indicated by "film" in Fig.7 is the measurement result with only the retardation film sandwiched between the polarizer and the reflector. It shows large dispersion. Even though the dispersion of the retardation film is large, nevertheless the chromatic properties of the display is much better than normal STN. The white light contrast ratio is more than 45. It should be even better with wide band retardation films.

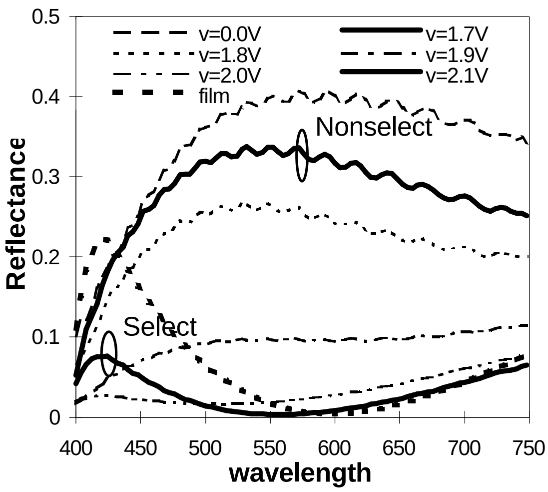

Fig.7 Experimental results of fully compensated RSTN

Conclusions

A chromatic parameter space representation (CPS) is proposed and demonstrated. The real appearance of the display, with both chrominance and luminance, can be visualized. One advantage of the CPS is the ease of modeling the display in any situation, with any number of optical elements incorporated. We have shown that the CPS is very useful in identifying the operating modes of various LCDs, both transmissive and reflective.

Of great significance, different kinds of LCDs, like TN, OMI, SBE and STN can be systematically presented in one diagram or a set of diagrams. Similarly reflective displays such as HFE, TN-ECB, MTN, SCTN, RTN and RSTN can all be seen together in the CPS. The parameter space presents more choices for designing the displays. As examples, two new designs of LCDs with good performance are proposed. In conclusion, it is shown that CPS is very powerful in searching for new LCD display modes, especially when chromatic dispersion is concerned.

Acknowledgment

This research was supported by the Hong Kong Industry Department.

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