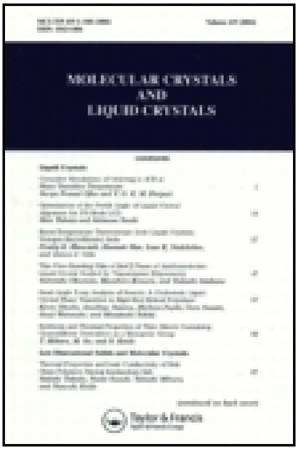

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Viewing Angle Dependence and Optimisation of the SSFLCD for Full Colour LCD TV

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Abstract If the Surface Stabilised Ferroelectric LCD[1] is to seriously threaten the position of the CRT it is essential that it offers full colour performance over a wide angle of view.

The dependence of transmission as a function of wavelength on viewing angle has been calculated by solving numerically the equation for the effective refractive indices and path length using polar coordinates. Experimental measurements on a thick (8.1 micron) and a thin (2.1 micron) cell are presented in agreement with the theoretical predictions.

The deviation in hue and colourfulness (saturation) as a function of cell spacing variation is also studied and results plotted on the CIE 1931 Chromaticity diagram. They indicate that very high tolerances in cell spacing uniformity are required and that even with optimum cell spacing the viewing cone is restricted.

A solution is proposed to greatly improve the viewing cone and ease the constraint on cell spacing tolerance by introducing a multigap structure of the type suggested to reduce the effect of dispersion in the TN displays. Theoretical results are presented.

INTRODUCTION

The Surface Stabilised Ferroelectric LCD[1] has attracted much attention because it offers the potential speed and memory to produce a complex display refreshed at video rates suitable for TV applications. It is axiomatic that a television display should faithfully reproduce the colour stimuli of the original scene. For example, the accurate colour rendering of the skin tones which form a major part of the colour information in television programmes is especially critical. Therefore, in order to seriously challenge the superiority of the CRT, the new technology must offer equivalent colour performance over a wide angle of view.

Unlike other display devices, the LCD is non-emissive and must be viewed either in reflection or transmission. For colour, the spectral distribution of the viewing light is important and so a colour LCD will normally be a transmission device with a light source having a controlled colour temperature.

For an ideal display, the liquid crystal between crossed polarisers placed in the light path would behave as a light gate with an achromatic response, i.e. in the 'bright' state, the colour and amplitude of the light would be unaffected as a result of passing through the crystal. In practice, contrast in the SSFLCD relies on the optical anisotopy (birefringence) of the liquid crystal and the reorientation of its optical axis when a electric field is applied. In the 'bright' state there is a phase retardation between the ordinary and extraordinary rays which is optimized so that when the display is placed between crossed polarisers maximum transmission occurs. The phase retardation is dependent on the wavelength, optical path length and the effective refractive indices experienced by the ordinary and extraordinary rays. It follows that for any SSFLCD used with a white light source in an additive or subtractive colour system:

1. There cannot be maximum cell transmission for all white source wavelengths simultaneously; so the colour temperature of the light will be modified to some extent in

passing through the cell.

2. For a given cell and light source, the colour temperature of an emergent ray will depend uniquely upon the cell spacing at that point.

3. The brightness and colour of the transmitted light will vary with viewing angle.

The mitigation of these effects is a challenging engineering problem which must be solved before the SSFLCD can be considered as a competitor of the shadow mask CRT.

THEORY

To investigate the angular dependence of the SSFLCD device we have considered the two 'ideal' bistable states of the SSFLCD, shown in figure 1, as slabs of uniaxial birefringent material whose optic axis has been rotated through 2α between the two states, where α is the smectic C layer tilt angle.

If the slab is placed between crossed polarisers then the 'dark' state is obtained when the optic axis is parallel to one of the polarisers, and the 'bright' state is optimised for maximum transmission when the optic axis is at 45 degrees (α = 22.5) to the polarisers and the conditions for constructive interference of the ordinary and extraordinary rays of light at normal incidence are satisfied, i.e.

$$T = T_o \operatorname{Sin} \left(\frac{\pi \Delta n d}{\lambda}\right) \qquad (1)$$

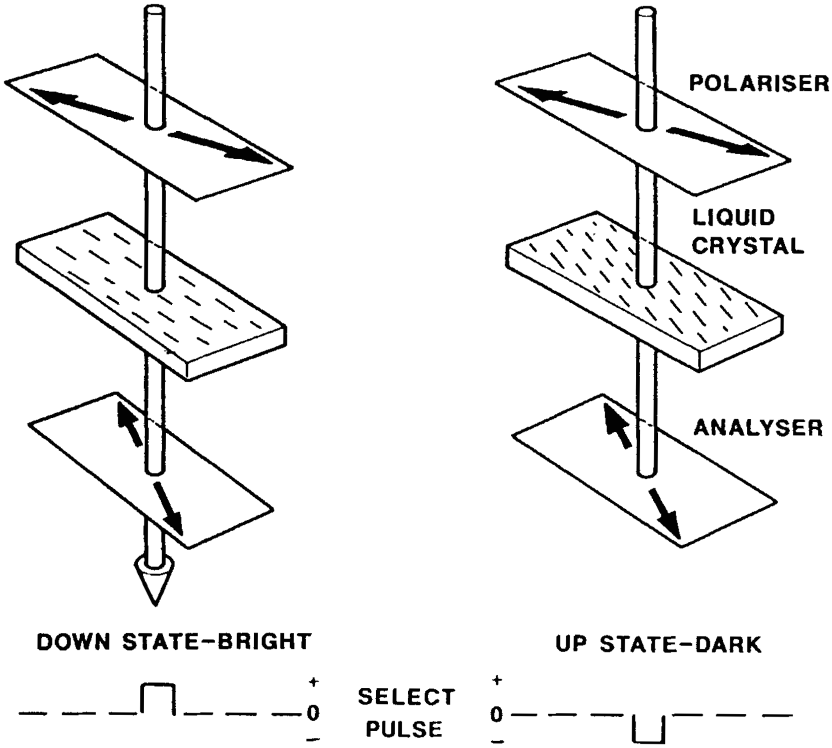


FIG 1 THE SSFLCD-OPERATING PRINCIPLES

where Δn (= n_e - n_o) is the birefringence, d is the cell spacing (path length), λ is the wavelength of light, and T is the percentage transmission assuming ideal polarisers.

However, if the device is viewed at an angle off normal incidence then equation 1 must be modified to take into account

1) the change in the effective birefringence;

2) the change in the effective cell spacing.
Both of these effects will be scaled by the wavelength of light transmitted and will therefore be different for red, green and blue pixels.

To consider light incident at angles off normal we define the polar coordinates θ, Φ, where θ is the angle between the direction of the incident ray and the normal to the slab, and Φ is the azimuthal angle defined from the extraordinary axis (the director $\underline{n}$) as shown in figure 2.

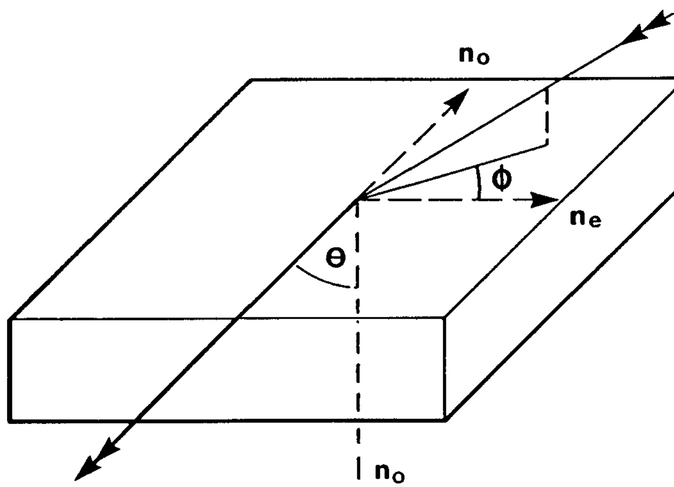


FIG 2 BIREFRINGENT SLAB

EFFECTIVE BIREFRINGENCE

Due to symmetry, the effective value of the ordinary refractive index n_o is independent of θ, Φ. However the effective value of the extraordinary refractive index n_{eff} which must be used to calculate the value of Δn in equation

1, is angular dependent. An expression for the value of n_{eff} as a function of Θ, Φ can be derived by constructing an ellipsoidal surface whose radius vector is equal to n_{eff}. It is constructed in the following way:

For light at normal incidence (Θ=0°) the electric vector of light which is transmitted through the polariser along the polarising axis at 45 degrees to n_e and n_o will be in the plane of the slab and undergo phase retardation according to equation 1.

For light at grazing incidence to the slab (Θ=90°) in a direction perpendicular to n_e(Φ=90°), a component of the electric vector of light transmitted along the polarizing axis is similarly in the plane of the slab and therefore $n_{eff} = n_e$.

However for light at grazing incidence (Θ=90°) in a direction parallel to n_e(Φ=0°), there will be no component of the electric vector of light transmitted in the plane vibrating parallel to n_e, and in this case we can write $n_{eff} = n_o$. i.e. no phase retardation will occur.

It is thus possible to construct an 'indicatrix' of n_{eff} in the device in the form of an oblate ellipsoid as shown in figure 3, where the two major axes are n_e and the minor axis is n_o. The value of n_{eff} can then be obtained as a function of polar coordinates Θ, Φ by determining the length of the vector OI from the centre of the ellipsoid along Θ, Φ to the intersection with the surface.

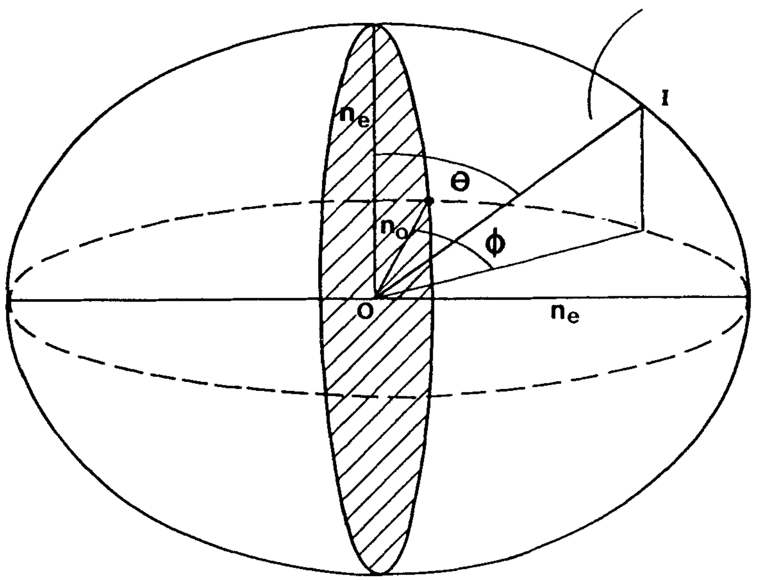
It should be noticed that the 'indicatrix' of n_{eff} for the device is not the same as the indicatrix of the refractive index for the slab alone.

Using the equation describing an ellipse we can write;

$$\frac{n_{eff}^2}{n_e^2}\cos^2\theta + \frac{n_{eff}^2}{n_e^2}\sin^2\theta\sin^2\Phi + \frac{n_{eff}^2}{n_o^2}\sin^2\theta\cos^2\Phi=1$$

rearranging gives;

$$n_{eff}^2 = \frac{n_e^2}{\left[1 + \left(\frac{n_e^2}{n_o^2} -1\right)\sin^2\theta\cos^2\Phi\right]} \quad (2)$$



VECTOR O I REPRESENTS LIGHT INCIDENT AT POLARS AT ANGLES θ,ϕ AS DEFINED IN FIG 2. THE LENGTH OF VECTOR O I IS THE EFFECTIVE EXTRAORDINARY REFRACTIVE INDEX (n_{eff})

FIG 3 AN INDICATRIX TYPE REPRESENTATION OF THE EFFECTIVE EXTRAORDINARY REFRACTIVE INDEX

REFRACTION AT LC INTERFACE

The angle of incidence, θ, is the angle of the light passing through the LC slab. This is related to the angle in air, θ(air), by Snell's law.

$$\sin\theta = \frac{\sin\theta air}{n_{lc}(\theta,\Phi)} \qquad (3)$$

where the value for n(LC) (ignoring double refraction) is approximately

$$n_{lc}(\theta,\Phi) = \frac{n_o + n_{eff}(\theta,\Phi)}{2} \qquad (4)$$

However as n_{eff} is angular dependent it is necessary to solve equations 2 and 4 numerically; this can be done by a simple convergent iteration procedure.

$$\text{Hence } \Delta n(\theta,\Phi) = \frac{n_e}{\{1 + (\frac{n_e^2}{n_o^2} - 1)\sin^2\theta\cos^2\Phi\}^{\frac{1}{2}}} - n_o$$

where Φ is measured from the direction of n_e.

EFFECTIVE PATH LENGTH

The effective path length d_{eff} is given by

$$d_{eff} = d/\cos\theta \qquad (5)$$

where θ is the angle of incidence in the LC slab (corrected for refraction).

The viewing angle dependence of colour was computed on the basis of equations 2-5 for a 8.1 microns thick cell and a 2.1 microns thin cell for the red (620nm), green (540nm) and blue (470nm) wavelengths at incident angle θ = 45° and azimuthal angles Φ = 0° - 360°. The birefringence values used in these calculations were those measured at the appropriate wavelength.

EXPERIMENTAL

The SSFLCDs used for the experimental measurements were half filled devices so that the abrupt LC-air interface could be used for obtaining independent measurements for the thickness and birefringence of the display. The thickness was measured using the optical interference created in the air side of the LC-air interface by a spectrum analyser. Using this thickness, the birefringence was calculated from the optical rotation produced in the LC side of the LC-air interface, measured using the Senarmont compensator technique. Measurements were made for a range of wavelengths, obtained by using narrow band filters, to obtain the variation in birefringence with wavelength (figure 4). The experimental angular dependence of the birefringence colours were made using a spot radiometer positioned at the appropriate angles relative to the display. All the results, both theoretical and experimental, were normalised to the maximum transmission of the red light (620nm).

RESULTS

Figure 5a shows the theoretical predictions for a thick (8.1 microns) display and figure 5b shows the experimental results for a display having the same thickness and birefringence.

As the thickness is decreased the theory predicts that the angular dependence of the colour decreases, as shown by figure 6a, for a (2.1 microns) thin display. This is confirmed experimentally by figure 6b.

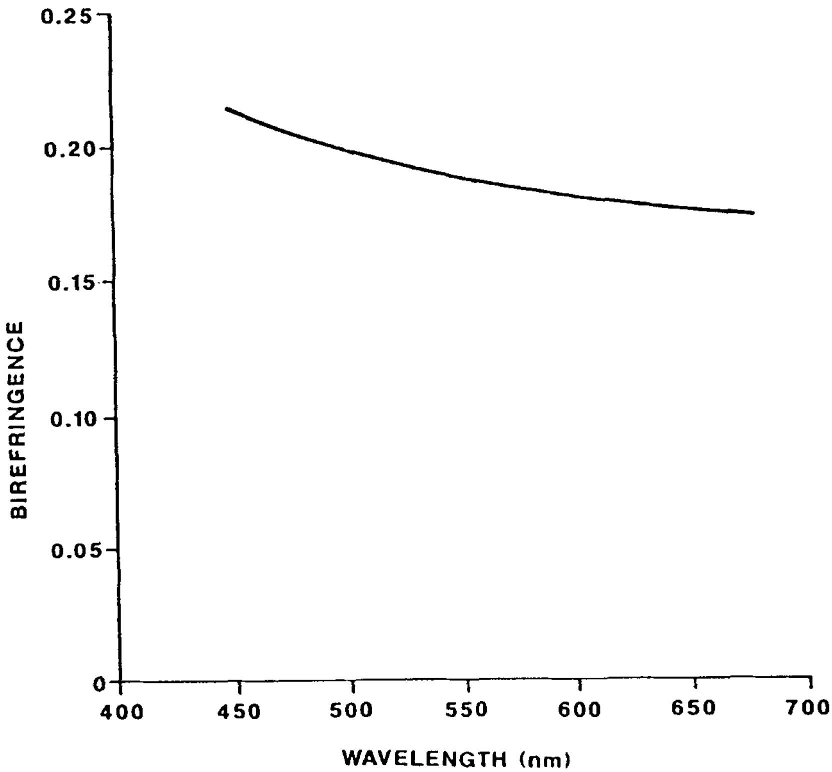
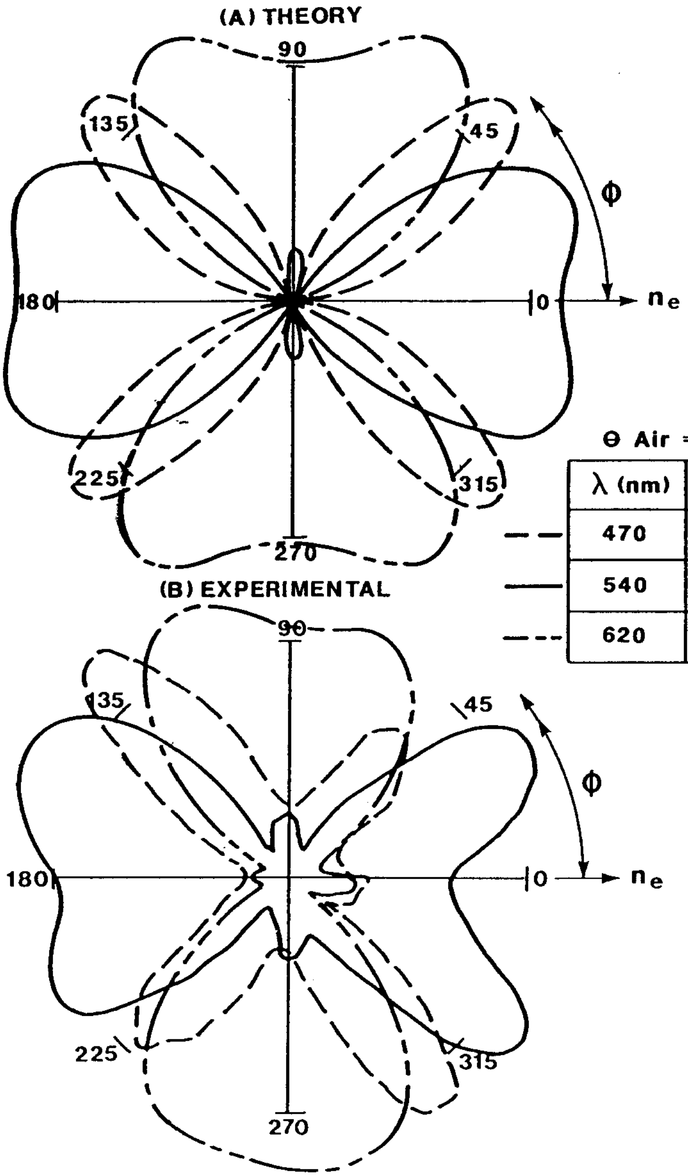


FIG 4 BIREFRINGENCE V WAVELENGTH

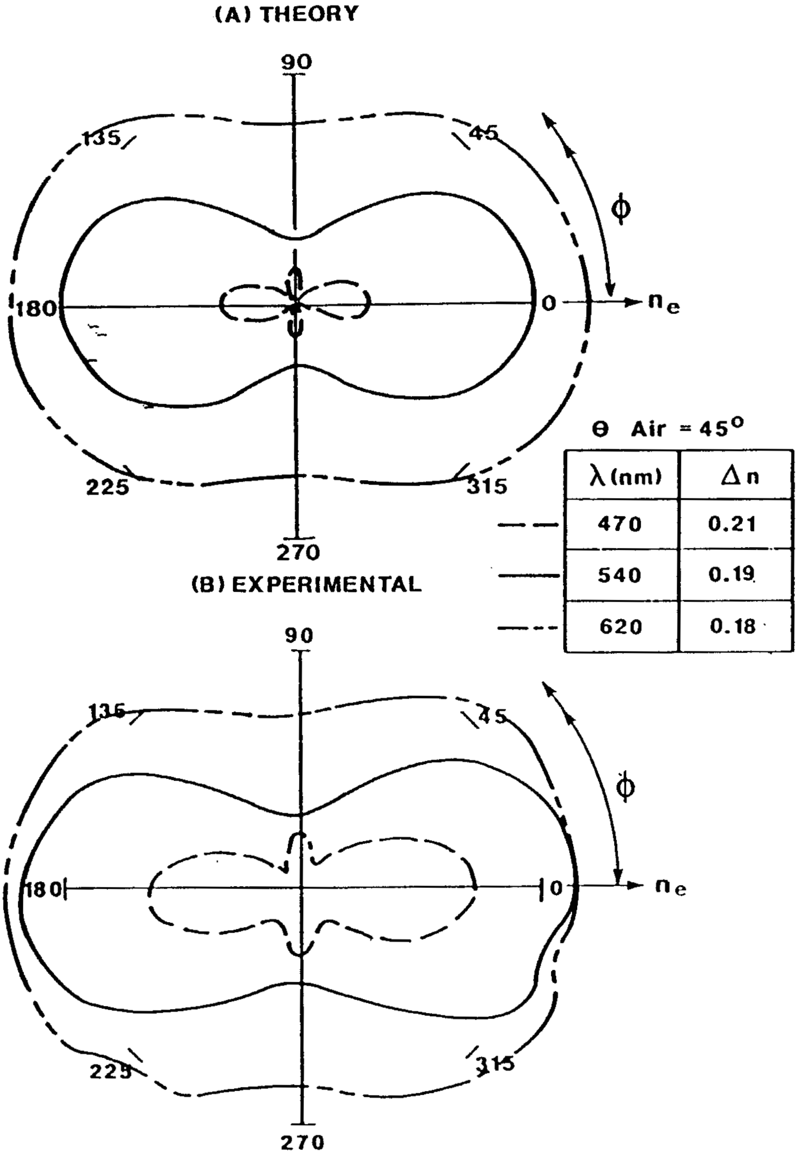
For the purpose of producing a usable display it is important to interpret these results in terms of perceived colour. This was done by using the IDEAL[2] computer program and regarding the SSFLCD as a filter with angular properties described by the above theory and combining it with an idealised line emission light source, where the intensities



Θ Air = 45°

	λ (nm)	Δ n
— —	470	0.21
——	540	0.19
— - -	620	0.18

FIG 5 VIEWING ANGLE DEPENDENCE OF A THICK (8.1μm) CELL



λ (nm)	Δn
470	0.21
540	0.19
620	0.18

FIG 6 VIEWING ANGLE DEPENDENCE
OF A THIN (2.1μm) CELL

of the line transmissions are adjusted to give a normal incidence transmission equivalent to D6500 light source. The resultant colour transmission as a function of viewing angle and with a 10% spacing tolerance was plotted on the 1931 CIE chromaticity diagram (see figures 7 and 8). The ellipse (figure 8) defines the chromaticity limit for the D6500 source (British Standard 950: 1967).

By constructing a display having a stepped or multigap structure similar to that used in active matrix displays, where the thickness of the RGB pixels are different, each one being optimised for its own colour, the angular dependence of each of these RGB pixels becomes identical in the ideal case, and hence the variation in colour with the angle would be eliminated (see figure 9). Figure 10 shows that by using a multigap type structure the dependence of colour on thickness variation would also be reduced.

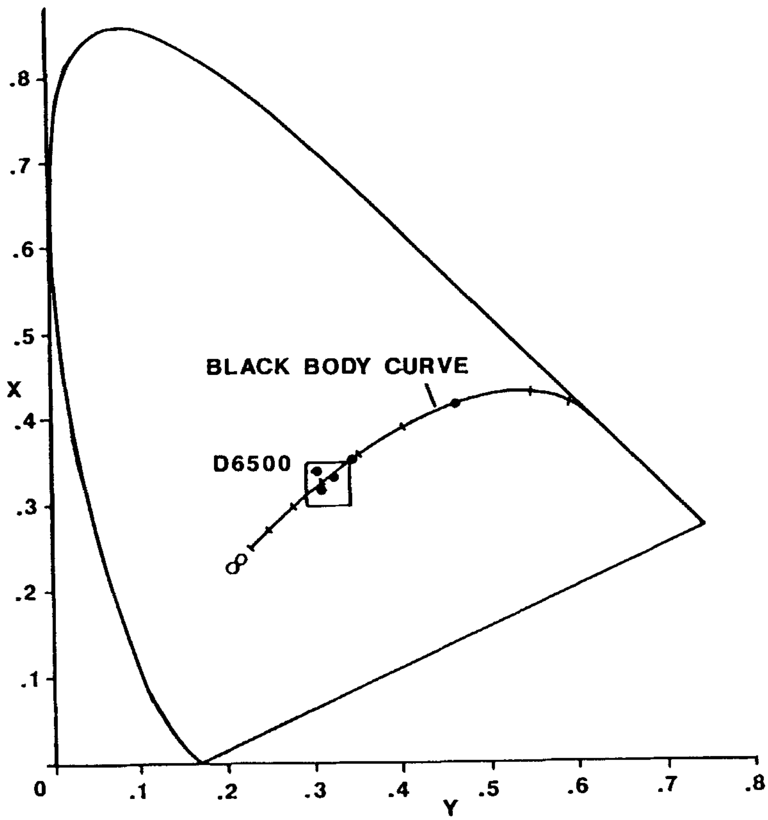
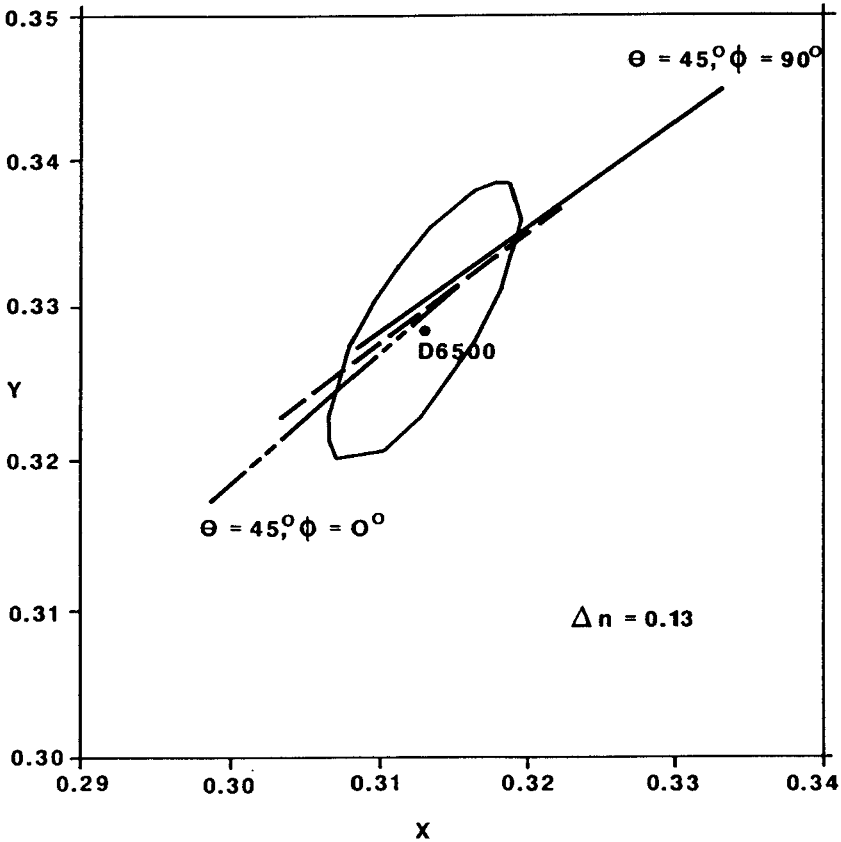
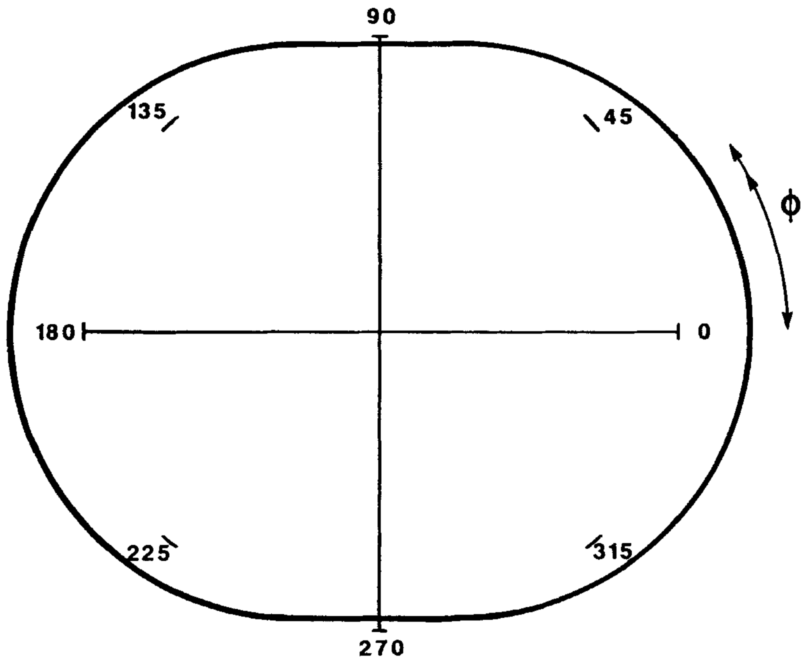


FIG 7 CIE (1931) CHROMATICITY DIAGRAM



COLOUR TRANSMISSION FOR A 1.7μm CELL WITH A SPACING TOLERANCE OF ± 10% AS A FUNCTION OF VIEWING ANGLE

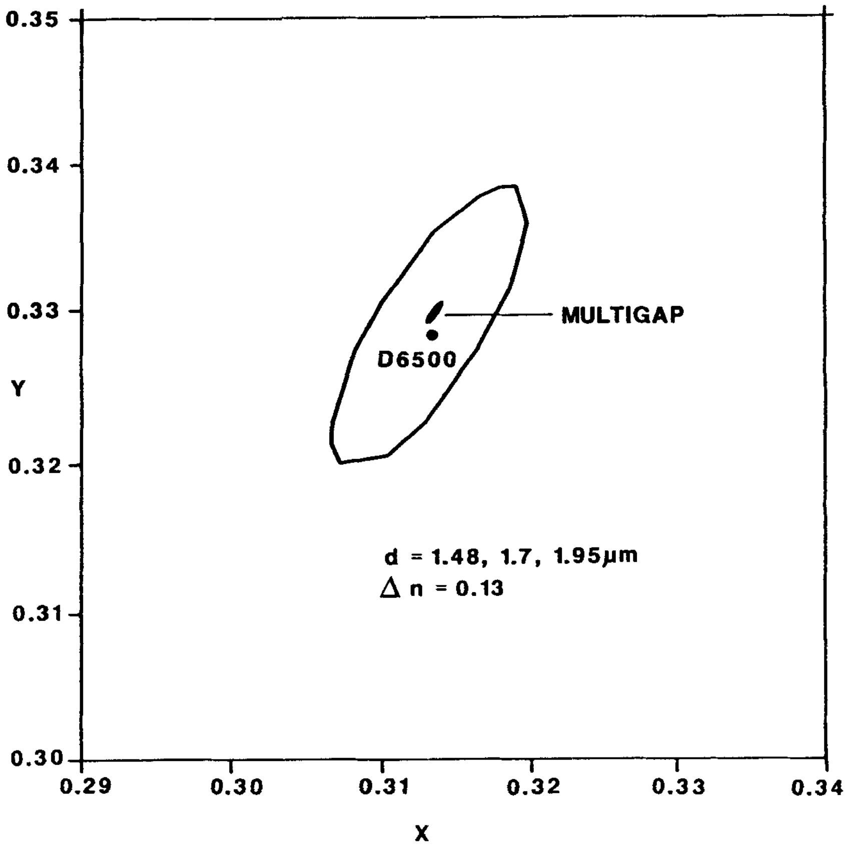
FIG 8 CHROMATICITY CO-ORDINATES CIE 1931 DIAGRAM



θ Air = 45°

λ(nm)	d	Δn
470	1.48	0.21
540	1.70	0.19
620	1.95	0.18

FIG 9 THEORETICAL VIEWING ANGLE DEPENDENCE FOR A MULTIGAP CELL



COLOUR TRANSMISSION FOR A MULTIGAP CELL WITH A SPACING TOLERANCE OF ± 10% AS A FUNCTION OF VIEWING ANGLE

FIG 10 CHROMATICITY CO-ORDINATES CIE 1931 DIAGRAM

DISCUSSION

For a given SSFLCD the transmission of light of a particular wavelength depends on the optical path length (i.e. the cell spacing, viewing angle and birefringence, equation 1). The transmission through a 2.1 micron cell with a spacing tolerance of 10% at the three wavelengths red (620nm), green (540nm) and blue (470nm) is shown in figure 11. It can be seen that the rate of change of transmission with cell spacing is different for each wavelength, thus, in order to maintain a colour balance that is acceptable for use in television it is critical to maintain uniform cell spacing and to restrict the viewing cone.

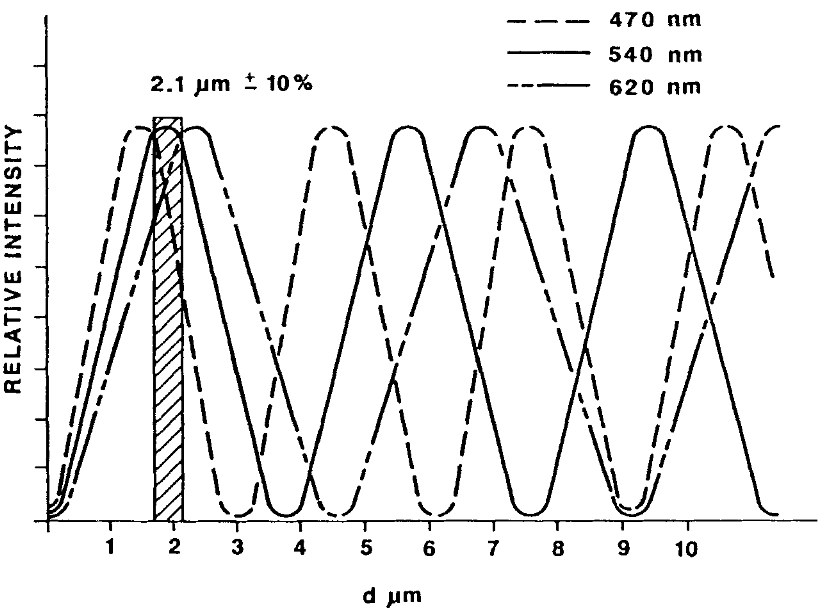


FIG 11 COLOUR SEPARATION AND CELL THICKNESS IN FLCD WITH $\Delta n = 0.13$

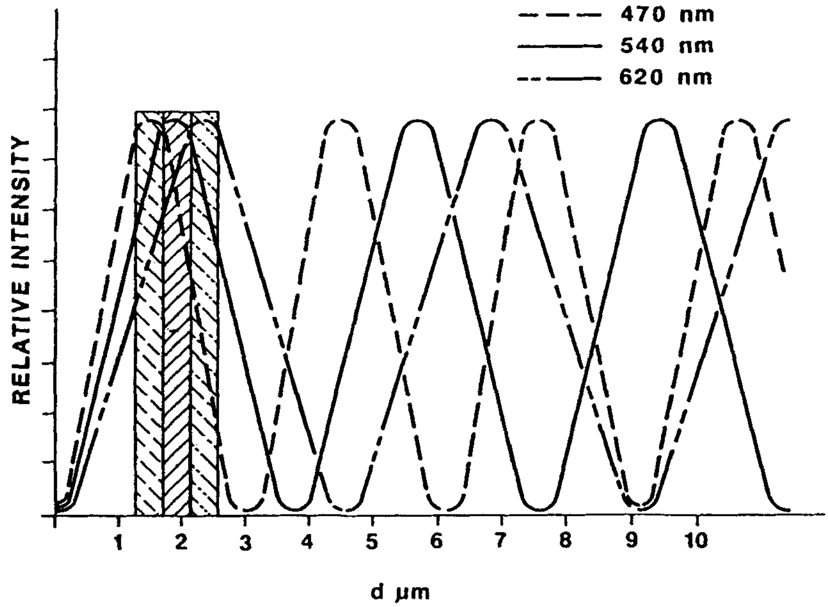


FIG 12 COLOUR SEPARATION AND CELL THICKNESS IN FLCD WITH $\Delta n = 0.13$

The cell spacing in a multigap structure can be optimized such that the transmission through each pixel is the same (figure 12). Thus any change in viewing angle or cell spacing will result in little change in the hue (colour), although the brightness will change. For the luminances used in television the eye is more sensitive to changes in hue than in brightness, therefore a multigap cell with a spacing tolerance of 10%, which can be achieved practically, will produce a display with a viewing cone acceptable for use in television. However, in practice a multigap structure is more complex to fabricate and may give rise to problems in multiplexing across LC layers of different thickness. This is currently under investigation.

In calculating the angular dependence on colour ideal states have been assumed, but in practice they may be twisted or tilted[4]. Some experimental results (figure 5b) show systematic deviations from the idealised case (figure 5a) depending upon the surface alignment treatment of the cell and it may be possible to use this technique to identify states. This is currently under investigation.

CONCLUSION

We have shown that it is possible to model the viewing angle characteristics of a SSFLCD.

From this model and the experimental results it is seen that to achieve high specification colour performance over wide viewing angles required for television applications it is possible to introduce a multigap structure with cell spacing to a tolerance of +/- 10%.

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