Behaviour of effective optical axis of IPS mode under driving voltage

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Abstract
Although color characteristics of IPS mode are much better than TN or VA mode, there still remains a room for improvement of the color characteristics of IPS mode compared with the conventional CRT. It has been generally assumed that inherent color variation of IPS mode is entirely owing to dependence of the effective retardation on wavelength and role of optical axis of IPS mode has been little considered. In this study, we investigated the effects of driving voltages on the effective retardation and the effective optical axis by a computer simulation. The result shows that rotation of effective optical axis is dependent on wavelength and tends to be smaller for larger wavelength.

1. Objectives and Background
As usage of LCD display increases, the exact color reproduction is becoming more important, especially for high-end application. Necessity to improve the color characteristics of LCD still remains, though the performance gap with the CRT is decreasing. Widely used LCD mode such as TN, IPS and VA mode show different color characteristics due to the different LC configuration.

IPS mode[1] can be treated as a uniaxial medium sandwiched between two crossed polarizers. Transmittance of this simplified model can be written as follows.

$$T = \sin^2(2q_t(V))\sin^2(pd\Delta n(l)/l)$$

where q_t is the angle between optical axis of uniaxial medium and entrance polarizer, V is the driving voltage and λ is the wavelength of the transmitted light. The first sine term of right side of the above equation is related to the optical axis and independent of wavelength. The second sine term is related to the retardation of LC cell.

In the above model, the driving voltage only affects the optical axis of LC. As the second sine term is not affected by the driving voltage, the transmittance ratio between different wavelength is constant irrespective of driving voltage. Therefore, once the ratio due to the second terms is compensated by factors such as Backlight wavelength distribution and color filter transmittanc, no color variation should be observed on the normal direction of IPS. So this model is not accurate enough to describe the color variation observed in the IPS mode. T. Satake [2] suggested a more sophisticated model by describing the effective refractive index n_{eff} as a function of driving voltages as follows

$$T = \sin^2(2q_t(V))\sin^2(pd\Delta n_{eff}(l,V)/l)$$

Yet, he mentioned little about the effect of the wavelength.

In this study, we investigated the effects of driving voltages on the effective retardation and the effective optical axis for a given wavelength by using a computer simulation to understand the cause of color dependence in IPS mode.

2. Result
By performing computer simulation with a commercial 2D LCD simulator, we calculated the Stokes vectors for the red, green and blue lights of 450, 550 and 650 nm wavelengths under various driving voltages of IPS cell of electrode width 4um and electrode distance 5um.

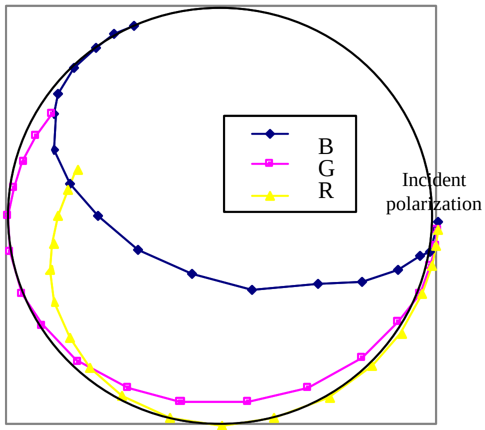

Figure 1. Position of Stokes vector on Poincare sphere for different wavelength under driving voltage. Center of the circle corresponds to the pole of Poincare sphere.

In Poincere sphere of Figure 1, Stokes vectors are located on the right side of circle at zero voltage. As the voltage increases, Stokes vectors gradually move to the left side. If the effective optical axis of 450,550 and 650nm light are the same at the specific voltage, Stokes vectors of these wavelengths can be connected by the straight light, but Figure 1 does not show such a trend.

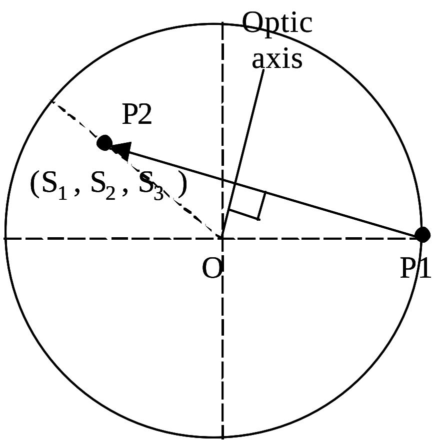

Fig 2. Rotation of Stokes vector by a retarder on Poincare sphere. Center of the circle correspond to the Pole of Poincare sphere.

From Stokes vectors, the effective optical axis and the effective retardation values are determined. As shown in Figure 2, a uniaxial retarder uniquely defines the value of Stokes vector. At maximum transmittance, optical axis of 450, 550 and 650 nm wavelength are calculated to be 54, 45, 41 degrees.

From the result, we confirmed that the rotation angle of the effective optical axis depends on the wavelength and has a tendency to be smaller for the larger wavelength. LC molecule barely moves near the alignment layer by the strong anchoring energy and LC inside the cell does not rotate with the same azimuth angle. (Figure 3)

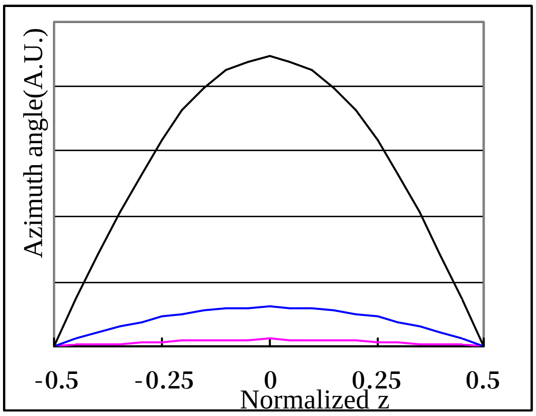

Figure 3. Azimuth angle of LC molecules along the cell gap direction z at various voltage

This twisted LC structure can be treated as multiple layers of different optical axis and the same retardation value. When azimuth angle distribution is symmetric, corresponding Jones Matrix representation can be approximated as [3]

$$W_T \approx \mathbf{I} - i\sin\Gamma_0 \sum_{n=1}^{N} \mathbf{M}(f_n)$$

$$= \mathbf{I} - i\sin\Gamma_0 \begin{pmatrix} \sum\cos 2f_n & \sum\sin 2f_n \\ \sum\sin 2f_n & -\sum\cos 2f_n \end{pmatrix}$$

where f_n is the optical axis of each sublayer. And the effective optical axis can be written as

$$\sin^2 2f = \frac{B^2(A^2 \sin^2 \Gamma_0 + 1)}{A^2 + B^2}$$

$$\propto \frac{B^2}{A^2 + B^2}\left\{A^2\left(\Delta n/l\right)^2 + 1\right\}$$

where $A = \sum \cos 2f_n,\ B = \sum \sin 2f_n$

The above approximate equation shows the relation between the effective optical axis f and the wavelength.

In-plane twist of LC molecule affects the phase of the incident light of different wavelength, differently and is the cause of color variation.

3. Impact

In this study, we analyzed the cause of color variation in IPS mode by computer simulation. We verified that the rotation of the effective optical axis depends not only on the driving voltages but also on the wavelength. These dependency of the effective optical axis as well as the effective refractive index on the wavelength cause the color variation in IPS mode.

4. Acknowledgements

We thank our colleagues in Anyang R&D center for their support.

5. References

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[2] T.Satake, T.Nishioka, T.Saito, T.Kurata, Jpn.J.Appl.Phys. 40, 195 (2001)

[3] To be published .