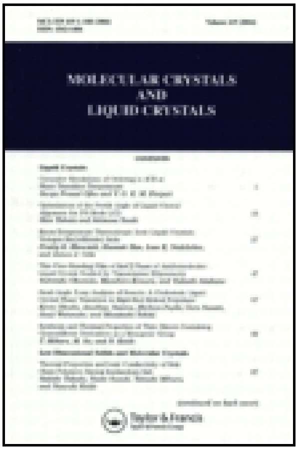

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High utilization efficiency of ambient light is needed for the design of the bright reflective LCDs. In transmissive mode, the brightness can be easily controlled by a backlight. However, the light intensity of the reflective mode is limited within the ambient light. The loss of the incident light in the reflective mode results in darkening the LCD panel. It is an important point for the reflective display to increase the brightness as high as possible. In order to improve the efficiency, the property of a polarizer is discussed and the guideline is presented.

Keywords: reflective LCDs; backlight-less; linear polarizer; reflection

INTRODUCTION

Reflective color LCDs are important key devises in future information oriented society. The reflective LCD does not use a backlight. The backlight consumes electric power about one third of the transmitted LCDs. Therefore the long available time of a buttery is useful for the communication with anybody in anywhere, anytime. Backlight-less device realizes an energy saving world. Design of reflective mode needs a high efficiency of utilization of the ambient light for the bright display. In the transmissive mode, the brightness can be easily controlled by the backlight. However, the light energy in the reflective mode is limited within the ambient light. The loss of light is resulted in darkening of the display panel. It is an important point of the design of the reflective display. Many LCD modes in the reflective display with high performance have been discussed and developed in recent years [1]. In order to improve the efficiency of the ambient light, the reflectance of the panel must be increased as high as

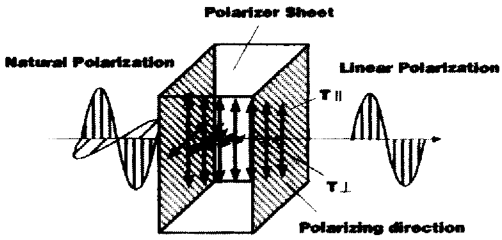
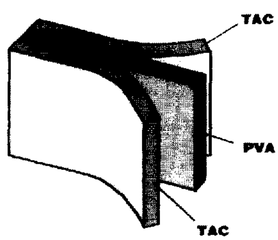


Figure 1 Principle of a polarizer.

possible. Therefore all components in the reflective device must be designed in the optimum conditions. A polarizer is an optical device which converts the incident natural polarized light to the linearly polarized light as shown in Figure 1 and is an essential component for the LCDs. Usually, the property of the polarizer has not been discussed in detail. However, the optical analysis of the polarizer is necessary for the improvement of the optical property. In this paper, the evaluation of the polarizer is discussed precisely and the design concept for the reflective display is clarified.

SURFACE REFLECTION

As shown in Figure1, a polarizer converts natural incident light to linear polarized light. It is an important optical component for LCDs. $T_{\perp}$ and $T_{\parallel}$ are transmittances of absorption maximum and minimum direction, respectively. Precisely speaking, there are reflection effects on the surfaces of the polarizer sheet. An ideal polarizer absorbs 50% of the incident light. The loss of the incident light is not able to ignore for the



Figuzre 2 Structure of a polarizer.

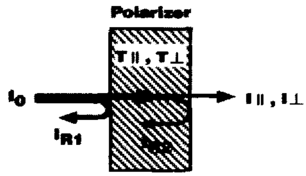


Figure 3 Definition of light components.

design of LCDs. In order to improve the brightness of display, Uchida et al. proposed the surface controlled reflector method for the reflective mode [1]. Even if the display used a polarizer, this method realizes the brighter display than a white paper. Generally, the linear polarizer is evaluated by the transmittances under the parallel and the crossed polarizer. The condition was considered that the ideal rotation of optical polarization occurs in the optical switching. When a both of ratio is large, the contrast ratio is high. In the reflective mode, the brightness must be designed as large as possible.

Basically, the polarizer is constructed with three layers as shown in Figure 2. The central sheet is a PVA sheet containing anisotropic material of absorption, such as dichroic dyes and iodine molecules. The central parts is sandwiched with two TAC layers for protection. The reflectance R is determined by the refractive indices of the two materials, the polarizer and the air. Therefore, the reflection occurs at the front and back surfaces of the polarizer. In the Figure 3, I_0 is intensity of the incident light, I_{R1}

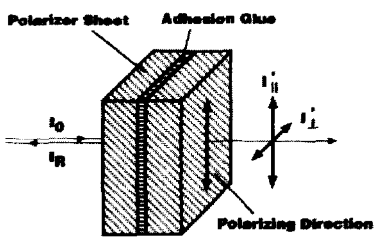


Figure 4 Configuration of stacked polarizers.

and I_{R2} are intensity of the reflected light at front and back planes, respectively. I_{II} is intensity of the transmitted light in transmissive axis, and $I_{\perp}$ is intensity of the direction in absorption axis. As the results, T_{II} and $T_{\perp}$ are expressed as the following equations;

$$I_{II} = I_0 \left(1-R\right)^2 T_{II} \cdots\cdots\cdots\cdots (1)$$

$$I_{\perp} = I_0 \left(1-R\right)^2 T_{\perp} \cdots\cdots\cdots\cdots (2)$$

T_1 and T_2 are defined as apparent transmittances parallel and perpendicular to the transmissive axis of the polarizer, respectively. These values involve the effect of the reflection.

$$T_1 = \frac{I_{II}}{I_0} = \left(1-R\right)^2 T_{II} \cdots\cdots\cdots (3)$$

$$T_2 = \frac{I_{\perp}}{I_0} = \left(1-R\right)^2 T_{\perp} \cdots\cdots\cdots (4)$$

The transmittances of the calculation are not considered the separation of the reflective components. The polarizer evaluation needs the calculation of three unknown parameters. Consequently, the equations (3) and (4) require one more independent equation for the separation of the optical components. As shown in Figure 4, two stacked polarizers is considered. If the air layer exists between two polarizers, the equations are square of each equations (3) and (4), and are not independent. Then, we considered that the polarizer sheets are stacked such that the boundary of the sheets are glued by the adhesive material with adjusted refractive index. In this case, no reflection occurred between the two polarizers and the following independent equations are obtained;

$$T_3 = \frac{I_{II}'}{I_0} = \left(1-R\right)^2 T_{II}^2 \cdots\cdots (5)$$

$$T_4 = \frac{I_{\perp}'}{I_0} = \left(1-R\right)^2 T_{\perp}^2 \cdots\cdots\cdots (6)$$

In the condition of the equation (6), very high precision measurements are required in the experiment. Because the value of $T_{\perp}^2$ is very small and is beyond of the precision

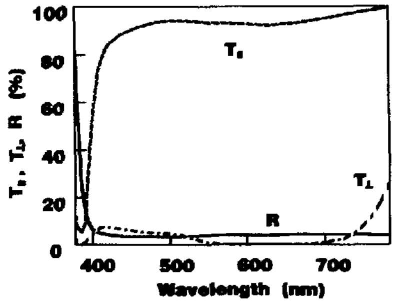


Figure 5 Wavelangth dependence of transmittances $T_{\parallel}$, $T_{\perp}$ and reflectance R considering with reflection.

the spectroscope. Therefore, $T_{\parallel}$, $T_{\perp}$ and R can be obtained as follows;

$$T_{II}=\frac{T_3}{T_1} \cdots\cdots\cdots\cdots (7)$$

$$T_{\perp}=\frac{T_2 \cdot T_3}{T_1^2} \cdots\cdots\cdots\cdots (8)$$

$$R=1-\sqrt{\frac{T_1^2}{T_3}} \cdots\cdots\cdots\cdots (9)$$

As the results, it is clarified that the practical transmittances $T_{\parallel}$, $T_{\perp}$ and the reflectance R can be calculated by the equations (7), (8) and (9).

Figure 5 shows $T_{\parallel}$, $T_{\perp}$ and R obtained from the experimental results. In order to match the reflective indices n=1.47 of the polarizer sheet (TAC film), a special adhesive

Table 1 Optical property of the polarizer.

Condition	Transmittance (%)			Polarizing Coefficiency
	Single	Parallel	Crossed	
As Measured	44.8	38.9	1.570	96.0
Considering Reflection	47.5	49.0	0.516	99.0

Polarizer: $T_{\parallel}$=93.9%, $T_{\perp}$=1.10%, R=4.19% Wavelength (nm): 550nm

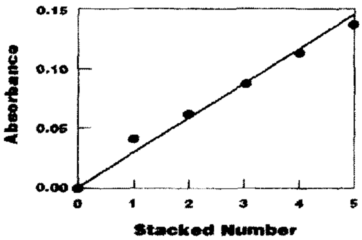


Figure 6 Stacked number dependence of absorbance.

material is used. This layer prevents the internal reflection of two polarizers. The reflective component is 4.2% in the visible region. Generally, the reflection of the boundary of two materials is obtained by the following equations.

$$R = \frac{(n_1 - n_2)^2}{(n_1 + n_2)^2} \cdots\cdots\cdots (10)$$

n_1 and n_2 are indices of two materials. This value is reasonable as the reflection between the TAC film and the air. T|| in non-absorbing direction is given as 93.3% and has 2.5% loss of the incident light. Table 1 shows the effect of the reflection components on the optical property. The results shows that the analyzed reflection effect shows higher polarizing efficiency than the values as measured.

OPTICAL DESIGN OF POLARIZER

Optimizing of optical characteristic for a polarizer is considered in this section. Figure 6 shows the stacked number dependence on absorbance. In the experiments, the polarizer sheets are stacked such that the boundary of sheets is glued by the adhesive material with adjusted reflective index. The internal reflection is eliminated. The linear

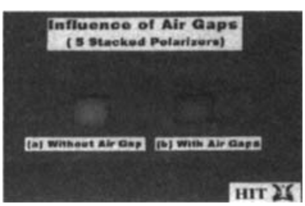


Figure 7 Fabricated panels of 5 stacked polarizers.

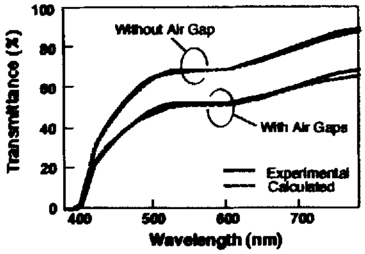


Figure 8 Wavelength dependence on the transmittance of 5 stacked polarizers.

relationship between the stacked number and absorbance is recognized. The stacked number corresponds to this phenomenon. This indicates that the Lambert-Beer's law is applicable to the design of the polarizer.

In order to clarify the reflection effect, we fabricated 5 stacked polarizers with air gaps and without air gap as shown in Figure 7. The panel (a) without air gap is brighter than the panel (b) with air gaps. Figure 8 shows wavelength dependence on the transmittance of 5 stacked polarizers. The calculated values are obtained by considering the Lambert-Beer's law. The experimental values coincides well with the calculated values. The air gaps induce considerable decrease of the transmittance. Figure 9 shows a color diagram of 5 stacked polarizers. The chromaticity coordinates are almost same between without air gap and with air gaps. This is easily understood from Figure 5 in which the reflection is constant value in the visible region.

Figure 10 shows the relationship between $T_{\parallel}$ and $T_{\perp}$ of the polarizer supposing the Lambert-Beer's law [2]. The parameter D is a dichroic ratio ($\log T_{\perp} / \log T_{\parallel}$) of the

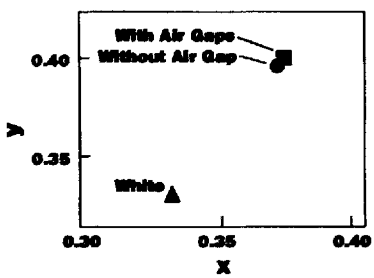


Figure 9 Color diagram of 5 stacked polarizers with air gaps and without air gap.

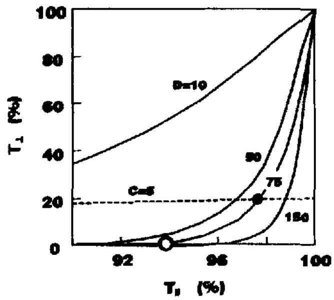


Figure 10 Relationship between $T_\parallel$ and $T_\perp$ of the polarizer. D and C are the dichroic ratio and the contrast ratio[2].

polarizer. D=75 is a measured value in the experiments. Usually, the polarizer is the optical device which converts the incident natural polarized light to the linearly polarized light as shown in Figure 1 and is an essential component for the LCDs. Usually, the contrast of a newspaper is about 5. For the reflective mode, the contrast ratio C=5 is considered as the target value. The dashed line shows this condition. 97.6% indicated by a black dot is the satisfied value for the condition of C=5 and D=75. There is possibility that the transmittance of the polarizer will be improved with 3.6% higher transmittance compared with a conventional one (a white circle) for the reflective LCDs.

Many materials are stacked in the LCD panel. The reflection in the cell is occured in not only polarizer but also other interfaces. As shown in Figure 11, the reflectance is

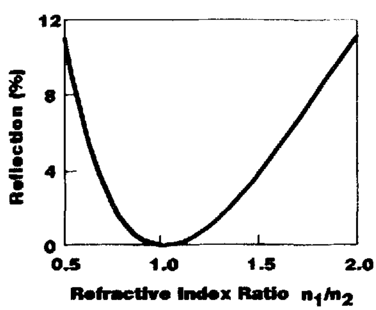


Figure 11 Refractive index dependence on reflectance.

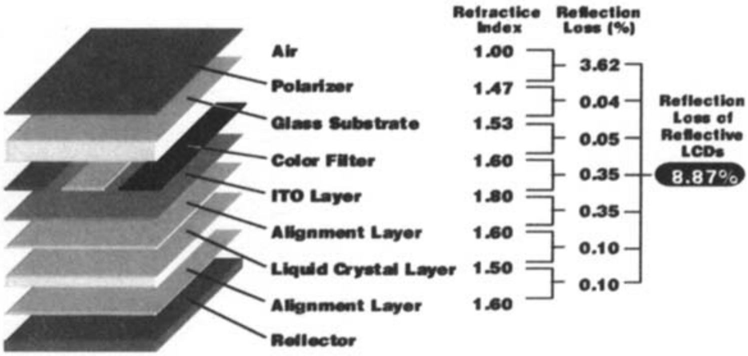


Figure 12 Reflection losses in the typical LCD structure.

determined by the ratio of the refractive indices n_1 to n_2. This relation is obtained from Equation (10). Figure 12 shows the reflection losses in the typical LCD structure. The total reflection loss of the reflective LCD are 8.87% in this case. If all the light of the reflection loss reaches to a viewer, the panel contrast does not able to exceed about 10. This effect is severe for the reflective LCD. Therefore, the precise design of the reflective LCDs is needed and the reflection loss must be as low as possible.

CONCLUSION

The evaluation of the linear polarizer is discussed. Considering the reflection loss, the improvement of the polarizer property is suggested and the guideline for the design is presented.

Acknowledgment

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