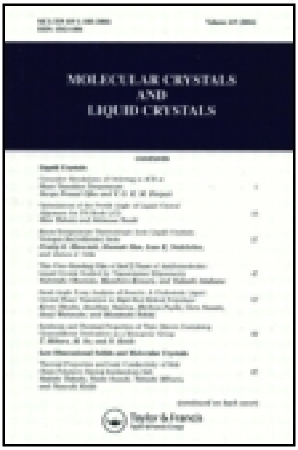

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Evaluation of Optical Parameter in Liquid Crystal Layer

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Liquid crystal displays (LCDs) are widely used in many fields for high performance, such as low power consumption, high contrast and high durability. The precise design of electro-optical performance and the controllability of the manufacturing technology in LCDs have progressed. The evaluation technology is indispensable to achieve the demand. Measurement of the retardation is one of the important evaluation technologies. It is closely related to the contrast, the viewing angle, the response speed and so on. A newly developed Senarmont method is proposed. This method gives more precise measurement accuracy and is useful the development of the LCDs performance.

Keywords: extinction angle; liquid crystal display; quarter wave plate; retardation; Senarmont method

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1. INTRODUCTION

Market of flat panel displays is growing rapidly according to the large information display area compared with CRT displays. Especially, liquid crystal displays are widely used in many fields for high performance such as low power consumption, high contrast, and high durability. In 2010 year, the LCDs market is estimated to a hundred billion dollars including from a miniature display to a super large projection display.

Now, the improvement of the performance of the LCDs, such as the contrast, the reproducibility of colors and the large display area, is required with the spread of the application fields. The interesting subject of the LCDs is response speed for the moving image. For the purpose of reducing power consumption of liquid crystal display (LCD) systems it is necessary to reduce the power dissipation at the backlights and it directly results in request for improvement of total transmittance of liquid crystal (LC) cells. Color-field sequential refreshing (CFS) method is an answer to that since it eliminates the loss at the color filters of ordinary LCDs. Optically compensated bend (OCB) mode LC and light emitting diodes (LED) are available for this use and it is presumable that the power efficiency of LEDs will reach to that of cathode fluorescent lamps (CFL) in the very near future. We demonstrated an experimental display system using color-field sequential refreshing method has been developed in combination with OCB mode liquid crystal and an LED backlight [1–3]. Very good results related to the high performance display were obtained.

As mentioned abode, the precise design of electro-optical performance and the controllability of the manufacturing technology have progressed. The evaluation technology is indispensable to achieve the demand. Measurement of the retardation is one of the important evaluation technologies. The retardation value is closely related to the contrast, the viewing angle, the response speed and so on. Usually the interference method is available for the measurements. This method needs to know the wavelength dependence of the birefringence. Contrary to this, the Senarmont method is very simple because the method needs only an extinction angle with rotating an analyzer plate. The key point of this method is how accurate angle can be obtained. For example, one-degree deviation of the measurement angle courses 3.5 nm discrepancy to the true retardation. The deviation of the designed retardation directly causes contrast deterioration. The conventional method has 4 values in peak and valley angles to the rotation of the analyzer. We propose a new method modified by the Senarmont method. In this method, 8 data points are obtained with the analyzer rotation. This method gives more precise measurement accuracy and is useful the development of the LCDs performance.

2. CONVENTIONAL SENARMONT METHOD

The Senarmont method is one of the methods for the retardation measurement of the liquid crystal cell. The optical system of Senarmont method is constructed with a polarizer, a quarter wave-plate ($\lambda/4$) plate and analyzer as shown in Figure 1. The liquid crystal layer is placed between the polarizer and the analyzer. The incident linearly polarized light changes to the elliptically polarized light after passing through the liquid crystal layer with a birefringence. The quarter wave-plate ($\lambda/4$) is possible to give some retardation to the light convert to the linearly polarized light. As the analyzer is rotated in this system, the transmittance shows some extinct values. This means that the extinction angle gives the retardation of the liquid crystal layer. This method is so simple that it is used for the measurement of the retardation of the liquid crystal and the measurement such as thickness of a liquid crystal layer.

The light vector **E** passed through the Senarmont optical system is given by the Jones matrix as follows;

$$(\mathbf{E}) = \begin{pmatrix} \mathbf{E}_X \\ \mathbf{E}_Y \end{pmatrix} = \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} \cos\frac{\Gamma}{2} & -i\sin\frac{\Gamma}{2} \\ -i\sin\frac{\Gamma}{2} & \cos\frac{\Gamma}{2} \end{pmatrix} \begin{pmatrix} e^{i\frac{\pi}{4}} & 0 \\ 0 & e^{-i\frac{\pi}{4}} \end{pmatrix} \times \begin{pmatrix} \cos^2\theta & -\sin\theta\cos\theta \\ -\sin\theta\cos\theta & \sin^2\theta \end{pmatrix}. \tag{1}$$

where Γ is the phase difference, R is the retardation and λ is the wavelength. In this equation, the 4th term shows the linear polarizer and the 3rd term is the LCD material with the retardation Γ, the 2nd term is the effect of the quarter wave-plate and the first term is the effect of

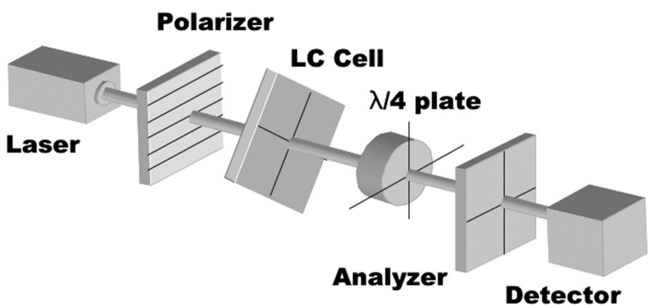

FIGURE 1 System of conventional Senarmont method.

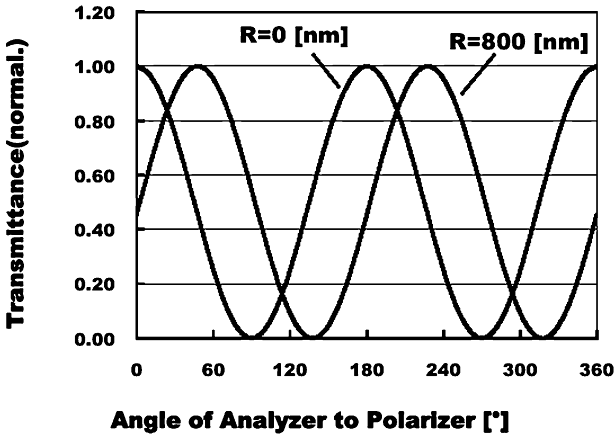

FIGURE 2 Rotation angle dependence on transmittance of the conventional Senarmont method in simulation.

the analyzer. The absolute value of **E** is corresponding to the intensity of the transmitted light T;

$$T = |\mathbf{E}_{\mathrm{X}}|^2 + |\mathbf{E}_{\mathbf{Y}}|^2 = \cos^2\left(\frac{\Gamma}{2} - \theta\right). \tag{2}$$

As the results, the extinction angle θ is expressed as follows.

$$\theta = \frac{\pi R}{\lambda} + \pi n \quad n = 0, 1, 2, 3, \cdots \tag{3}$$

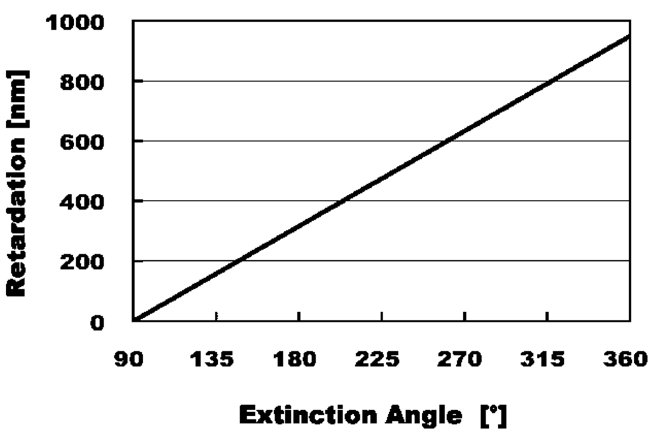

FIGURE 3 Extinction angle dependence on retardation value of liquid crystal layer in simulation.

Figure 2 shows the rotation angle dependence on the transmittance of the conventional Senarmont method in the simulation. It is assumed that the wavelength of the light is 632.8 nm. The 360°. rotation of the analyzer gives 2 extinction points. Increase of the retardation brings that the waveform shifts toward the right direction with the increase of the retardation value of the liquid crystal layer. Figure 3 is the extinction angle dependence on the retardation value of the liquid crystal layer in the simulation. The retardation is proportional to the extinction angle. The increase one-degree of the extinction angle gives 3.5 nm increase of the retardation value. The one nm accuracy of the retardation is realized by satisfying 0.75 degree accuracy in the extinction angle measurement.

3. MODIFIED SENARMONT METHOD

In order to minimize the error of readability of the analyzer angle, we considered one method in this paper. Usually, the retardation is determined by the extinction angle. More sampling points of the extinction angle give higher accuracy. We considered as the following method. The retardation value of the reflection mode changes twice, but the inclination rate 3.5 nm/degree in Figure 1 does not change. Then the improvement of the accuracy could not be realized in this method. If the output analyzer rotates 90 degrees, the form shifts to 180 degrees and the retardation peaks and valleys exchange each other. Then the combination with the parallel and crossed Nicols has twice valleys in the 360 degrees rotation of the analyzer. In actual, the system of the newly modified Senarmont method is considered as shown in Figure 4. The incident light form the laser to the mirror passes through the parallel Nicol configuration. Contrary to this, the crossed Nicols configuration affects to the reflected light.

We simulated the light propagation by the Jones matrix. The result is shown in the following equation;

$$(\mathrm{E}) = \begin{pmatrix} \mathrm{E_X} \\ \mathrm{E_Y} \end{pmatrix} = \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} \cos\frac{\Gamma}{2} & -i\sin\frac{\Gamma}{2} \\ -i\sin\frac{\Gamma}{2} & \cos\frac{\Gamma}{2} \end{pmatrix} \begin{pmatrix} e^{i\frac{\pi}{4}} & 0 \\ 0 & e^{-i\frac{\pi}{4}} \end{pmatrix}$$
$$\times \begin{pmatrix} \cos^2\theta & -\sin\theta\cos\theta \\ -\sin\theta\cos\theta & \sin^2\theta \end{pmatrix} \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \begin{pmatrix} \cos^2\theta & \sin\theta\cos\theta \\ \sin\theta\cos\theta & \sin^2\theta \end{pmatrix}$$
$$\times \begin{pmatrix} e^{i\frac{\pi}{4}} & 0 \\ 0 & e^{-i\frac{\pi}{4}} \end{pmatrix} \begin{pmatrix} \cos\frac{\Gamma}{2} & i\sin\frac{\Gamma}{2} \\ i\sin\frac{\Gamma}{2} & \cos\frac{\Gamma}{2} \end{pmatrix} \begin{pmatrix} 1 \\ 0 \end{pmatrix}. \tag{4}$$

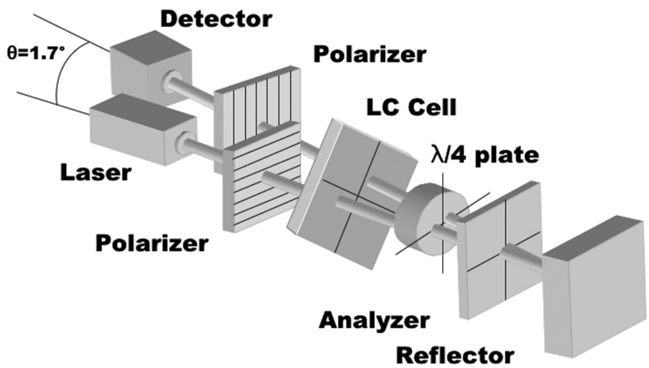

FIGURE 4 System of newly modified Senarmont method.

The right side of an equal sign has 9 terms. The center term represents the reflection effect of the mirror. From the equation, the transmitted light **T** is expressed as follows;

$$T = |E_X|^2 + |E_Y|^2 = \frac{1}{4}\sin^2(2\theta - \Gamma). \tag{5}$$

As the results, the extinction angle θ is expressed as follows;

$$\theta = \frac{\pi R}{\lambda} + \frac{1}{2}\pi n \quad n = 0, 1, 2, 3, \ldots \tag{6}$$

Figure 5 shows the rotation angle dependence on the transmittance of the modified Senarmont method in the simulation. The transmittance is modulated by the $\sin^2$ term. Compared with Figure 2, the modified Senarmont method has the extinction states with 90 degrees interval of the analyzer rotation. Figure 6 shows the comparison of the rotation angle dependence on the transmittance of two Senarmont methods in simulation. The retardation value is considered as 0 nm. This is not essential problem and the given retardation value shifts the waveform to the right direction at the rate of 3.5 degrees/nm.

The peak value of the transmission in new method has one forth in the conventional method. This form is caused by the product of the $\cos^2$ term for the incidence and $\sin^2$ term for the reflection terms. Figure 7 shows the discrepancy of the rotation angle dependence on the transmittance in two Senarmont methods near the extinction angle. The data coincides with each other within 10 degrees at the extinction angles. At the extinction angle that one of the terms of $\cos^2$ term or $\sin^2$ term becomes zero, another term has almost one near

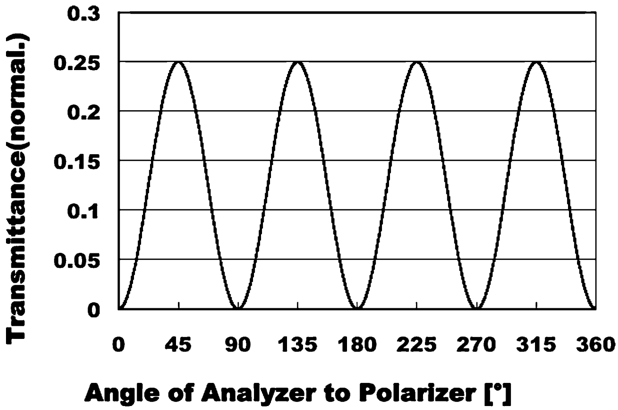

FIGURE 5 Rotation angle dependence on transmittance of the modified Senarmont method in simulation.

the extinction angle. So that, the accuracy of the new method is same as the conventional method for one measurement point.

In order to confirm the simulated results by experiments, the conventional Senarmont method is constructed at first as shown in Figure 1. The He-Ne laser (wavelength: $\lambda = 632.8\,\text{nm}$) was used for the light source. The Gram-Thomson laser prism has extinction rate 10,000 in our experiments. A sensitive tint plate (indicated

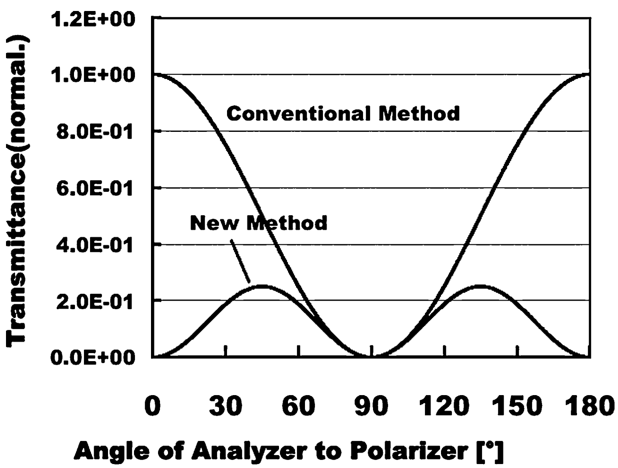

FIGURE 6 Comparison of rotation angle dependence on transmittance of two Senarmont methods in simulation.

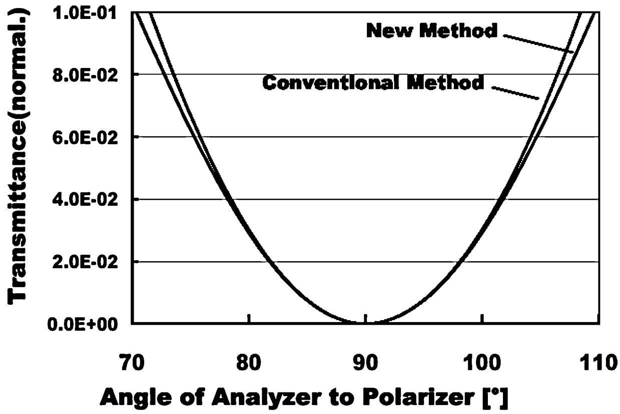

FIGURE 7 Discrepancy of rotation angle dependence on transmittance of two Senarmont methods in simulation.

retardation: R = 530 nm) was use for a retardation specimen. Figure 8 is the experimental results of the rotation angle dependence on the transmittance in the conventional Senarmont method. The difference of the rotation angles with minimum values is 180 degrees.

Figure 9 is the results for the newly modified Senarmont method. In this experiment, the optical system as shown in Figure 4 was used. The angle between the incident ray and the reflection ray is 1.7 degree. This value brings the error of the retardation measurement within 1 nm. Usually, this retardation value is enough for the design

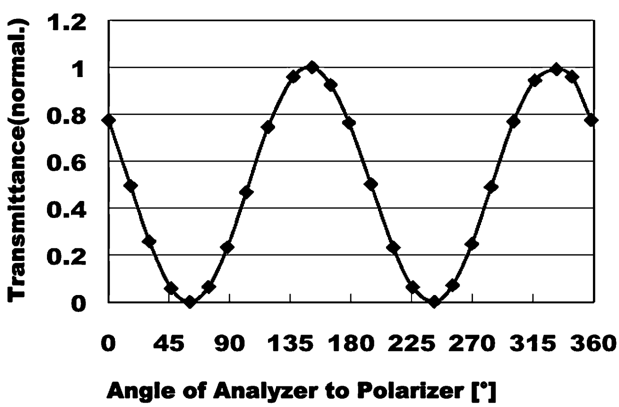

FIGURE 8 Experimental results of rotation angle dependence on transmittance in the conventional Senarmont method.

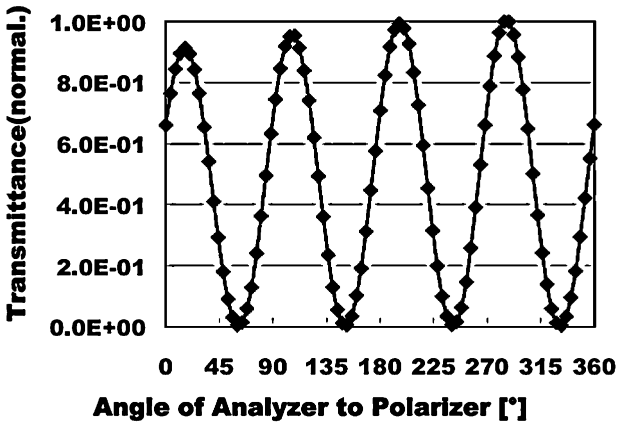

FIGURE 9 Experimental results of rotation angle dependence on transmittance in the newly modified Senarmont method.

of the liquid crystal display. Because the retardation is about 750 nm (birefringence: $\Delta n = 0.15$, thickness of the liquid crystal layer: $d = 5\,\mu m$), 1 nm of the retardation corresponds to 0.067 μm of the cell thickness. The difference of the rotation angles with the minimum values is 90 degrees in Figure 9. Figure 10 shows the experimental results of the rotation angle dependence on the transmittance in the newly modified Senarmont method near the extinction angle. The extinction angles are read as 60.45, 150.20, 240.44 and 330.45 degrees. From this data, the retardation is calculated as 528.95 nm. As the results, the theoretical prediction of the modified Senarmont method is confirmed. The retardation of the quarter wave plate is measured with the crossed polarizers by birefringence method. The measured result is 536 nm. This means that the experimental accuracy must be more improved. However, this paper proposes a modified Senarmont method with twice meaningful data compared with the conventional one. The theoretical analysis as shown in the equation (6) assists the new basic concept and the experiment shows the reasonable result.

The system of Figure 4 has a difficulty in space of the light source and the detector. The system of the newly developed Senarmont method is proposed in Figure 11. The beam splitter and the polarizer are added to the experimental configuration. The beam splitter works as the space separation of the light source and the detector. In the proposed method, a polarizer, a beam splitter and a mirror are added to the conventional Senarmont method. The accuracy of the optical

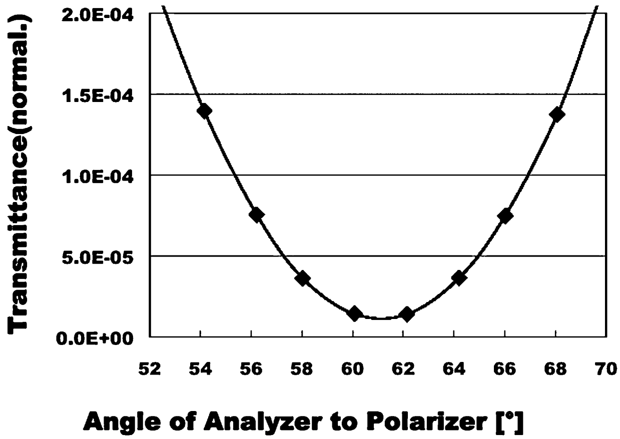

FIGURE 10 Experimental results of rotation angle dependence on transmittance in the newly modified Senarmont method near the extinction angle.

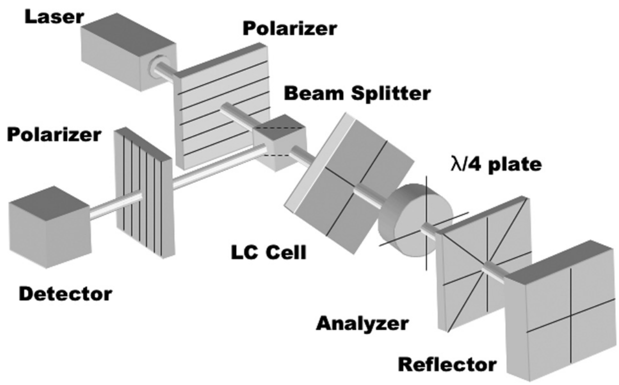

FIGURE 11 System of the newly developed Senarmont method.

measurement is improved by the following two procedures. The arrangement of an optical axis for the optical components is accomplished with the straight propagation of the light ray. The rotation angle is calibrated by the high extinction ratio of the polarizers and so on.

4. CONCLUSION

A new developed Senarmont method is proposed. In this method, twice sampling data are obtained by comparing with the conventional

Senarmont method. This method gives more precise measurement accuracy and is useful the development of the LCDs performance.

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