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FABRICATION AND ANALYSES OF NEGATIVE-BIREFRINGENT THIN FILM COMPENSATOR WITH CHARACTERISTIC MATRIX

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Fabrication et étude par matrice caractéristique d'un compensateur à biréfringence négative en couche mince

SUMMARY : We fabricated a multilayer negative-birefringent film as a phase compensator to minimize light leakage from twisted nematic liquid crystal displays in oblique incidence. The multilayer film stack is composed of alternating thin layers of silicon dioxide and titanium dioxide, which is magnetron sputtered on the glass substrates. The experiment agrees with the characteristic matrix calculation. Since each layer is not "thin" enough compared with visible spectra, the multilayer thin stack induces interference phenomena, and consequently reduces the transmittance. In order to eliminate the interference, we optimized the multilayer thin film to achieve high transmittance in the region of visible spectra.

RÉSUMÉ : Nous avons fabriqué un film compensateur biréfringent négatif multicouche pour minimiser les pertes lumineuses d'afficheurs à cristaux liquides nématiques en incidence oblique. Le film multicouches est composé d'un empilement alterné de dioxyde de Silicium et de Titane qui est déposé par pulvérisation magnétron sur des substrats de verre ;

Les expériences sont en bon accord avec les calculs par matrice caractéristique.

Comme chacune des couches ne peut être considérée comme « mince » en regard du spectre visible, l'empilement multicouches induit des phénomènes d'interférence et réduit de ce fait la transmission. Pour éliminer ces interférences nous avons optimisé le film mince multicouches pour obtenir une transmission élevée dans le visible.

INTRODUCTION

Thin film transistor twisted nematic liquid crystal display (TFT TN-LCD) is now one of the most popular high performance flat panel displays. However, the TFT TN-LCD has highly asymmetrical angular optical properties and poor contrast ratio at large viewing angles. Those drawbacks are caused by asymmetric arrangement of TN-LCD and anisotropic property of LC materials. To improve the viewing angles, methods such as two-domain divided TN cells [1], amorphous TN cells [2], bend cells [3], polymer stretched films [4], ultra-supertwisted LC's [5], and multilayer thinfilm coating [6] have been proposed.

Due to the anisotropic nature of LC materials, light leaks through the LC at large off-normal viewing angles in the dark state. Consequently, the leakage of light degrades the contrast ratio of LC displays. This light leakage can be suppressed by inserting a phase compensator between a TN cell and a polarizer of the LCD, acting as a negative birefringence film [7]. For optimum compensation, the phase retardation of the compensator is equal in magnitude but opposite in sign to the phase retardation of the LC layer in dark state. The whole structure then appears nearly isotropic, hence, oblique incident light will be blocked by the cross polarizers, and high contrast ratio can thus be obtained.

Multilayer thin film stack with alternating refractive indices can form negative-birefringence and implement as a phase compensator used in the LCDs [8]. This article reports on the fabrication of multilayer negative-birefringent films by magnetron sputtering and the analyses of the optical properties of the multilayer stack by a thin film characteristic matrix. We then optimize the whole multilayer structure to achieve antireflection (AR) in visible region in reducing the interference ripple. As a result, additional AR coating on top of the multilayer film becomes unnecessary.

MULTILAYER THIN FILM

Periodic structures of multilayer thin film stack can act as homogeneous birefringent materials if the wavelength of the incident radiation (λ) is much larger than the period (d) of the structure (i.e. $\lambda \gg d$). Rigorous calculation of the optical properties of this multilayer thin film stack is difficult, but under the condition of $\lambda \gg d$ we can calculate the optical behavior of multilayer thin film stack, as revealed by equivalent dielectric constants ε_e and ε_0

$$\varepsilon_e = \frac{1}{\dfrac{d_H}{d_H + d_L} \cdot \dfrac{1}{\varepsilon_1} + \dfrac{d_L}{d_H + d_L} \cdot \dfrac{1}{\varepsilon_2}}, \qquad (1)$$

$$\varepsilon_0 = \frac{d_H}{d_H + d_L} \cdot \varepsilon_1 + \frac{d_L}{d_H + d_L} \cdot \varepsilon_2 \qquad (2)$$

where ε_1 and ε_2 are the dielectric constants of the first and second layer, respectively; while d_H and d_L are their respective thickness. Since the equivalent dielectric constant is the same for all directions parallel to the stack (ε_0), but different for direction normal to the stack (ε_e), the assembly behaves as a uniaxial crystal with its optic axis perpendicular to the plane of the stack. The difference $\varepsilon_e - \varepsilon_0$ is always negative, according to Eqs. (1) and (2),

$$\Delta\varepsilon^m = \varepsilon_e - \varepsilon_0 = -\frac{q(1-q)(\varepsilon_1 - \varepsilon_2)^2}{(1-q)\varepsilon_1 + q\varepsilon_2} \leqslant 0, \qquad (3)$$

where $\Delta\varepsilon^m$ is the negative birefringence of the multilayer thin film, and $q = \dfrac{d_H}{D_H + d_L}$.

Normally white (NW) TN-LCD is a twisted nematic orientation for the field "off" state and can be treated as a homeotropic state for the field "on" state. The structure of the homeotropic state is close to a positive-birefringent film with the optical axis parallel to the field direction. On the contrary, multilayer thin film stack is negative-birefringent film, as demonstrated from the above approximation, with the optical axis normal to the film surface which can compensate the positive-uniaxial structure of NW TN-LCD field "on" state.

THIN LAYER CHARACTERISTIC MATRIX

As the compensator is composed by multilayer thin film stack, we can unveil the "negative-uniaxial property" of multilayer thin film stack by a thin layer characteristic matrix. The characteristic matrix for a homogeneous layer of refractive index N, optical admittance η, and physical thickness d is described as

$$M = \begin{bmatrix} \cos\delta & \dfrac{i\sin\delta}{\eta} \\ i\eta\sin\delta & \cos\delta \end{bmatrix} \qquad (4)$$

where the phase thickness δ is given by

$$\delta = \frac{2\pi}{\lambda} Nd\cos\theta \qquad (5)$$

optical admittance of tilted incidence with respect to each polarization is given by

$$\eta = N\cos\theta \quad \text{for s – polarization (TE)} \qquad (6)$$

$$\eta = \frac{N}{\cos\theta} \quad \text{for p – polarization (TM)} \qquad (7)$$

As the layer is "thin" enough compared with incident radiation wavelength, $Nd \ll \lambda$, the trigonometric function in Eq. (4) can be simplified as

$$M = \begin{bmatrix} 1 & \dfrac{i\delta}{\eta} \\ i\eta\delta & 1 \end{bmatrix}. \qquad (8)$$

For a combination of two thin layers, a high index (N_H, d_H) and a low index (N_L, d_L), the characteristic matrix is found by multiplying the respective characteristic matrices and dropping the high order terms in thickness as

$$M = \begin{bmatrix} 1 & i\left(\dfrac{\delta_H}{\eta_H} + \dfrac{\delta_L}{\eta_L}\right) \\ i(\eta_H\delta_H + \eta_L\delta_L) & 1 \end{bmatrix}. \qquad (9)$$

Comparing Eq. (9) with Eq. (8), we are able to identify an equivalent single layer to the high-low pair and obtain the equivalent optical admittance (η) and optical phase (δ)

$$\delta = \sqrt{(\delta_H\eta_H + \delta_L\eta_L)\left(\frac{\delta_H}{\eta_H} + \frac{\delta_L}{\eta_L}\right)} \qquad (10)$$

$$\eta = \sqrt{\frac{\delta_H\eta_H + \delta_L\eta_L}{\dfrac{\delta_H}{\eta_H} + \dfrac{\delta_L}{\eta_L}}}. \qquad (11)$$

For normal incidence, we get the characteristic matrix as

$$M = \begin{bmatrix} 1 & i\dfrac{2\pi}{\lambda}(d_H + d_L) \\ i\dfrac{2\pi}{\lambda}(N_H^2 d_H + N_L^2 d_L) & 1 \end{bmatrix} \qquad (12)$$

Defining total thickness as $D = d_H + d_L$, then the effective ordinary refractive index is given by

$$N_0 = \sqrt{N_H^2 \cdot \frac{d_H}{d_H + d_L} + N_L^2 \cdot \frac{d_L}{d_H + d_L}}. \qquad (13)$$

For oblique incidence, we can get

$$\delta_s = \frac{2\pi}{\lambda} N_0 \cos\theta_s (d_H + d_L)$$

$$\text{for s} - \text{polarization (TE)}, \qquad (14)$$

$$\text{where} \quad \cos\theta_s = \sqrt{\frac{N_H^2 d_H \cos^2\theta_H + N_L^2 d_L \cos^2\theta_L}{N_H^2 d_H + N_L^2 d_L}}$$

$$\delta_p = \frac{2\pi}{\lambda} N_0 \cos\theta_p (d_H + d_L)$$

$$\text{for p} - \text{polarization (TM)}, \qquad (15)$$

$$\text{where} \quad \cos\theta_p = \sqrt{\frac{d_H \cos^2\theta_H + d_L \cos^2\theta_L}{d_H + d_L}}.$$

It is easy to verify that θ_s is always smaller than θ_p and the retardation is negative. Therefore, when light is obliquely incident, the whole structure can be treated as a negative uniaxial crystal.

EXPERIMENTS AND RESULTS

A phase compensator film needs sufficient phase retardation depending on the application. To demonstrate the feasibility of the multilayer thin film compensator, we designed a compensator in which the phase retardation has reached to quarter-wave plate. The phase compensator was constructed by alternating thin layers of silicon dioxide and titanium dioxide that were magnetron sputtered on glass substrates. The refractive indices of silicon dioxide and titanium dioxide are 1.46 and 2.26, while the estimated values of ordinary and extraordinary indices from Eqs. (1) and (2) are $n_0 = 1.9$ and $n_e = 1.73$, respectively. The scanning electron microscopy (SEM) cross-sectional structure of the film unveils that the 0.975 µm thick multilayer is composed of a 32 nm period of alternating thin layers, as depicted in *figure 1.* Thus, the phase retardation of sixty thin layers is given by the product of the birefringence $\Delta n = n_e - n_0$ and the film thickness, i.e. $\Delta n \,.\, d = 0.166$ µm.

We calculated the normal transmittance of the multilayer stack as a function of wavelength using the characteristic matrix and compared with the measured results. As shown in *figure 2,* the dash and solid lines are the calculated normal transmittance with equal thickness of each layer and the measurement, respectively. The experiment agrees with the calculation, except in the shorter wavelength region, due to the fact that titanium dioxide is more absorptive near the UV region.

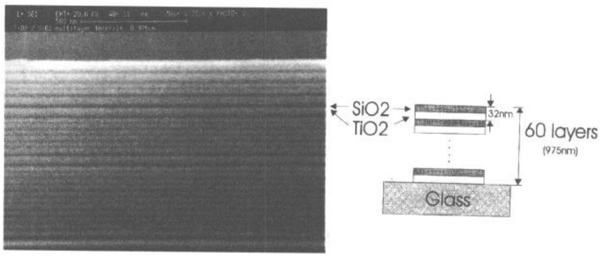

FIG. 1. — *Scanning electron micrograph (SEM) of multilayer thin film compensator. Total thickness is* 975 nm *and each layer is of* 16 nm *in thickness.*

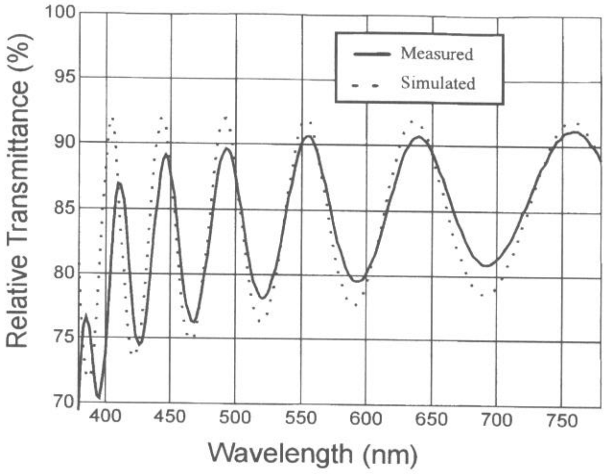

FIG. 2. — *Relative transmittance vs. wavelengths in normal incidence. Dash and solid lines are the simulated and measurement, respectively.*

To investigate the optical properties of the fabricated compensator, we measure the phase difference between TE and TM waves in oblique incidence by using He-Ne laser (632.8 nm). The sample was positioned between two cross polarizers. Rotated the sample to the direction of 45° to the polarizer to get the oblique incidence, transmitted intensity is then measured by a detector behind the analyzer. Relative transmittance as a function of the viewing angle is depicted in *figure 3* ; the star line is the measurement ; the solid line is derived from the characteristic matrix ; and the dash line is derived by treating the whole structure as a negative uniaxial crystal. The experimental result is close to calculation, but slightly different from the negative uniaxial approximation. This deviation reveals that the wavelength of the incident radiation is not much larger than the layer thickness (16 nm) of the stack. Hence, the multilayer thin film stack can not be treated as a pure negative uniaxial crystal structure.

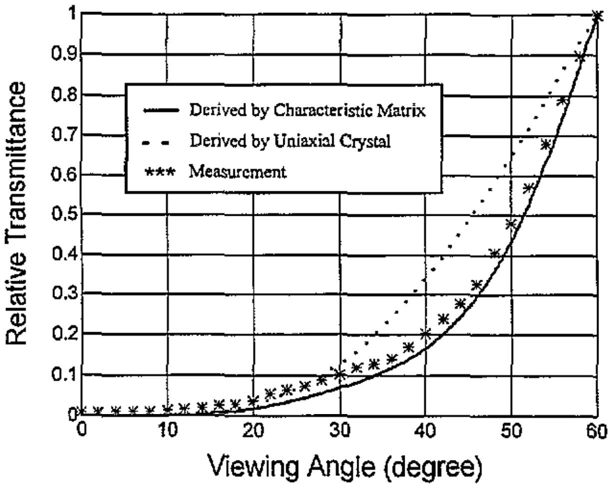

FIG. 3. — *Relative transmittance vs. viewing angles in the wavelength of* 632.8 nm. *Solid, star, and dash lines are derived from characteristic matrix, measurement, and derived by treating the whole structure as a negative uniaxial crystal, respectively.*

In order to eliminate the interference effect of the multilayer thin film, we optimize the whole structure so that reflectance of the thin film stack is suppressed within the entire visible spectra, instead of adding the AR coating on the top of the multilayer stack. After optimization, the transmittance of the multilayer stack is improved, as revealed in *figures 4a* and *4b* where transmittance is plotted as function of wavelength in normally incidence and function of viewing angle with reference wavelength 555 nm, respectively. The phase difference between TE and TM waves depends on the thickness of each layer in the multilayer stack. In the optimization process, the thickness of each layer has changed so that the multilayer stacks could possess AR function. As a result, the phase difference is also changed, as shown in *figure 5,* where solid and dash lines represent the phase difference before and after optimization, respectively. It is noted, as depicted in *figure 6,* that the phase difference dispersion (i.e. phase difference *vs.* wavelength) has changed as well. Solid and dash lines are calculated from the characteristic matrix before and after optimization, respectively, both at an incident angle of 45°. Above results are only theoretical consideration, the fabrication and performance evaluation of such phase compensators will be reported elsewhere.

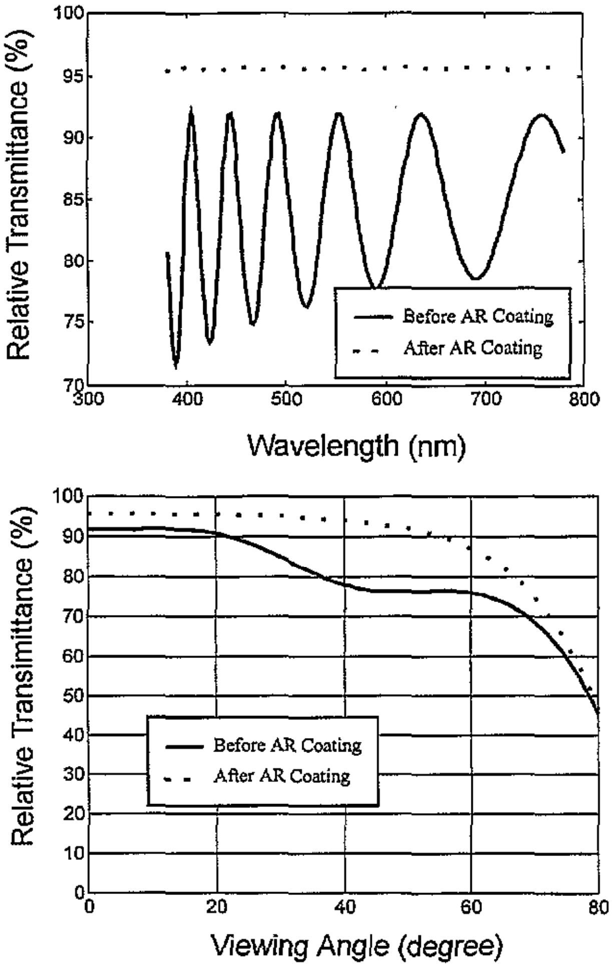

FIG. 4. — (a) *Relative transmittance vs. wavelengths in normal incidence.* (b) *Relative transmittance vs. viewing angles in the wavelength of* 555 nm. *Solid and dash lines represent the results before and after optimization, respectively.*

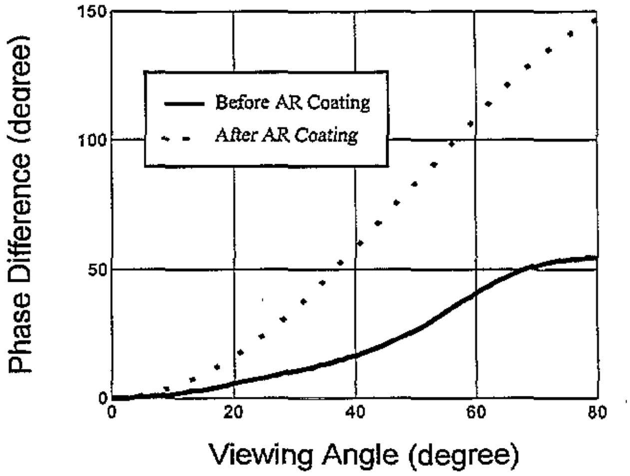

FIG. 5. — *Phase difference between TE and TM waves vs. viewing angles. Solid and dash lines represent the results before and after optimization, respectively.*

To achieve wide viewing angle for a full color display, good phase matching has to cover not only over a wide range of incident angles but also for all the color spectra employed [9]. Therefore, the birefringence of phase compensator film should have a similar wavelength-dependence as the LC film does. As shown in *figure 6,* the phase difference dispersion relationship can be modified by optimization process. Thus, the multilayer thin film compensators allow phase compensation for both viewing angle and wavelength for a LC cell to improve image quality of the TN-LCDs.

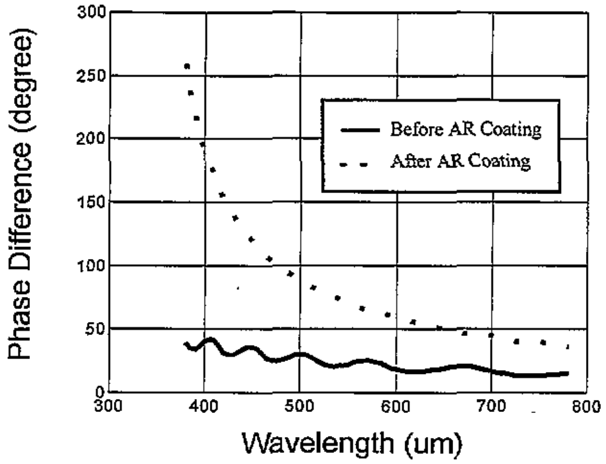

Fig. 6. — *Phase difference between TE and TM waves vs. wavelengths. Solid and dash lines are calculated from characteristic matrix before and after optimization, respectively, both at an incident angle of 45°.*

CONCLUSIONS

We fabricated a negative-birefringent thin film phase compensator by magnetron sputtering and analyzed their optical properties by characteristic matrix. If the layer thickness of the multilayer thin film stack is significantly less than the wavelength of incident radiation, then the birefringence can be determined by Eq. (3) and there is no interference loss. As the layer thickness (16 nm) is no longer "thin" compared with visible spectra, the degree of light leakage is closer to the characteristic matrix predicted rather than a pure uniaxial crystal approximation, therefore, interference occurs happen and interference loss is high.

Since there are ripples in the transmittance, we need to optimize the whole structure in order to minimize the interference effect. Optimization process results in higher transmittance, but causes the change in thickness of each layer and the relationship between phase difference and wavelength. A phase-matched negative birefringent film can therefore be designed and fabricated.

All dielectric multilayer thin film phase compensators made by magnetron sputtering possess sufficient phase retardation, low reflection loss, excellent mechanical strength, good uniformity over large area, and phase-matching with the employed LC. Those advantages of the all dielectric multilayer thin film phase compensator shall be a good candidate for improving the contrast ratio of LCDs over wide viewing angles.

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