A broadband wide-incident-angle reflective polarization converter

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Abstract — A high-performance reflective polarization converter which could be used in a backlight recycling system for liquid-crystal-display (LCD) devices is proposed. The device consists of a twisted-nematic (TN) liquid-crystal film, a uniaxial A-plate, and a reflector. The configuration parameters, such as thickness and orientation of the films, are optimized using a genetic algorithm. As a result, the design can convert light from TM to TE polarization (or TE to TM) at a maximum 99.7%, minimum 91.3%, and average 96.7% conversion efficiency for the entire visible spectrum and incident angle from 0 to 60°. Such a broadband reflective polarization converter is particularly useful for enhancing the light efficiency and reducing the power consumption of LCDs.

Keywords — *Polarization converter, liquid-crystal film, liquid-crystal display, light efficiency.*

DOI # 10.1889/JSID17.10.849

1 Introduction

In direct-view liquid-crystal displays (LCDs), two crossed absorption-type sheet linear polarizers are commonly used in order to obtain high contrast ratio.[1] Such a linear polarizer has strong absorption over the entire visible wavelength along its absorption axis. Especially, the bottom polarizer absorbs more than half of the unpolarized backlight because only the light polarized along the transmissive axis could pass through, while the light polarized in the orthogonal direction would be absorbed by the linear polarizer. By using two crossed linear polarizers, the maximum transmittance of an unpolarized backlight is limited to ~45%. Therefore, how to enhance the optical efficiency of LCDs is a practically important issue.[2]

A backlight recycling system could significantly improve the optical efficiency by replacing the bottom linear polarizer with a reflective polarizer.[3–5] In such systems, one linear polarization [e.g., p-wave, *i.e.*, TM (transverse-magnetic) wave] will pass through the reflective polarizer and the orthogonal component [s-wave, *i.e.*, TE (transverse electric) wave] will be reflected back for recycling. When the s-wave hits the rough surfaces of the diffusers and the diffusive reflector of the backlight system, its polarization state is changed to elliptical (a superposition of p-wave and s-wave). Similarly, the p-wave is transmitted and the s-wave is reflected by the reflective polarizer for recycling again. In each bouncing, less than half of the residual light is recycled and a small portion of light is either absorbed or scattered. Recently, Tsai and Wu reported a broadband wide-incident-angle reflective polarization converter using a metal grating to replace the diffusive reflector.[6] It can reach maximum 93.0%, minimum 48.0%, and average 87.2% conversion efficiency for a light spectrum from 400 to 700 nm and incident angle from 0 to 60°.

In this paper, we present a broadband, wide-incident-angle polarization converter, which has a simple structure and high conversion efficiency. It only consists of a TN film with anti-reflection (AR) coating, a positive A-plate, and a reflector. By optimizing the thickness and orientation of the optical components, it achieves maximum 99.7%, minimum 91.3%, and average 96.7% conversion efficiency as the incident wavelength varies from 400 to 700 nm and incident angle from 0 to 60°. High conversion efficiency enhances the total backlight recycling efficiency. It is particularly useful for an LCD backlight system, where the white light incidents from all directions.

2 Device configuration

Figure 1 shows the device configuration of this broadband wide-incident-angle polarization converter and Fig. 2 shows the orientation angles of the films. The AR film consists of multi-layers of isotropic materials. The bottom TN LC rubbing angle is β with respect to x axis, and the twist angle of the TN cell is ϕ. The slow axis of the uniaxial positive A-plate is set at an angle α with respect to x axis. The thicknesses of the TN film and A-plate are d and p, respectively, and these films can be laminated together to form a compact light-weight device. Generally speaking, the TN cell works as a broadband polarization rotator which is not sensitive to wavelength variation. The uniaxial film adds more degrees of freedom to the overall device configuration so that the design can be broadband and wide-view. All the optical components extend in the x–o–y plane, while the light incidents in the x–o–z plane at an angle θ, as Fig. 1 shows.

Revised extended version of a paper presented at the 28th International Display Research Conference (IDRC '08) held November 4–6, 2008, in Orlando, Florida, U.S.A.

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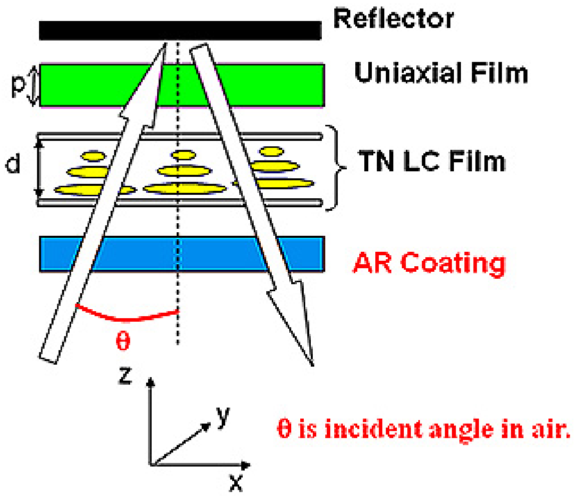

FIGURE 1 — Configuration of the polarization converter.

After optimization of the orientation and thicknesses of the films, TM-polarized incident light could be converted into TE (or TE to TM) at a conversion efficiency of more than 90% at any incident angle from 0 to 60° over the entire visible wavelength.

3 Simulation and optimization

We used the extended Jones matrix method[7,8] to simulate the reflected light, and then optimized the configuration using a genetic algorithm. We found that the extended Jones matrix method works very well by considering an ideal AR coating in the simulation. Afterwards, we confirmed the results using 4 × 4 matrix methods[9,10] and showed the effectiveness of simulation methodology using the extended Jones matrix method which is much more effective in a genetic search than the 4 × 4 matrix method. To facilitate calculation, the device is discretized into N layers as shown in Fig. 3. The first three layers are AR coating. The TN film is divided into many thin layers ($4 \sim N-1$), so that for each thin layer we can assume that the LCs are homogeneously aligned. Then, the TN cell could be treated as many thin layers of retarders with their optic axes rotating gradually in x–o–y plane. And the last layer is the uniaxial film.

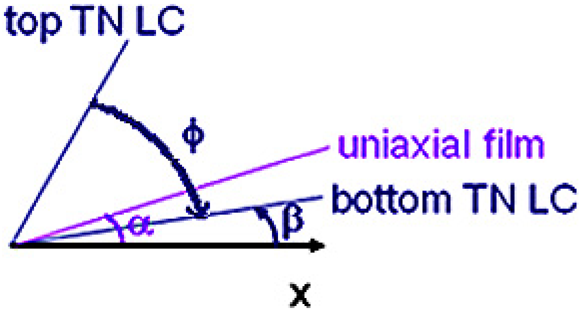

FIGURE 2 — Orientation angles of the films.

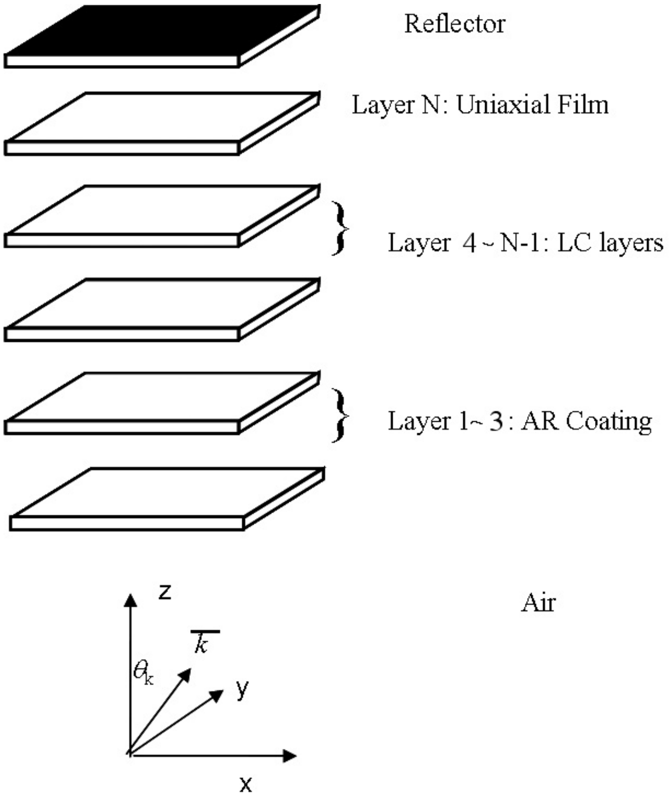

FIGURE 3 — Multilayered structure of the reflective polarization converter.

In extended Jones Matrix method, we assume the AR coating is an ideal coating, but in a 4 × 4 matrix method confirmation, we use the AR coating designed by the Chebyshev function. The TN material's refractive indexes are n_o = 1.50 and n_e = 1.60, and the uniaxial film n_o = 1.50 and n_e = 1.51, all at λ = 589 nm. During simulation, we took into account the dispersion of materials as[11]

$$\Delta n = G\frac{\lambda^2 \lambda^{*2}}{\lambda^2 - \lambda^{*2}}, \qquad (1)$$

where λ^* = 0.21 μm is the mean resonance wavelength.

In the optimization, we only calculated the normalized transmittance; all the absorption and reflection losses from films and reflector were ignored. After obtaining the normalized transmittance for the TE polarization component through the improved 2 × 2 extended Jones Matrix method described above, we can implement global optimization for wide-incident-angle and broadband design. In the global optimization, the cost function is taken to be

$$\text{cost} = \underbrace{\max}_{400\,\text{nm} \le \lambda \le 700\,\text{nm}} \left[\underbrace{\max}_{0 \le \theta \le 60^\circ} \left[1 - T_{TE}(\lambda, \theta)\right] \right], \qquad (2)$$

which is minimized in the search of β, ϕ, d, α, and p. Here, T_{TE} is transmittance of the TE component to the incident TM light and β, ϕ, d, α, and p are the orientation angles and thicknesses of the films as shown before in Figs. 1 and 2. In this work, we use a genetic algorithm (GA) for global optimization at first[12] and then use the conjugate gradient (CG) method[13] for local optimization. Although we have designed a broadband polarization converter in the past,[14] that design was a broadband transmissive device with normal incidence

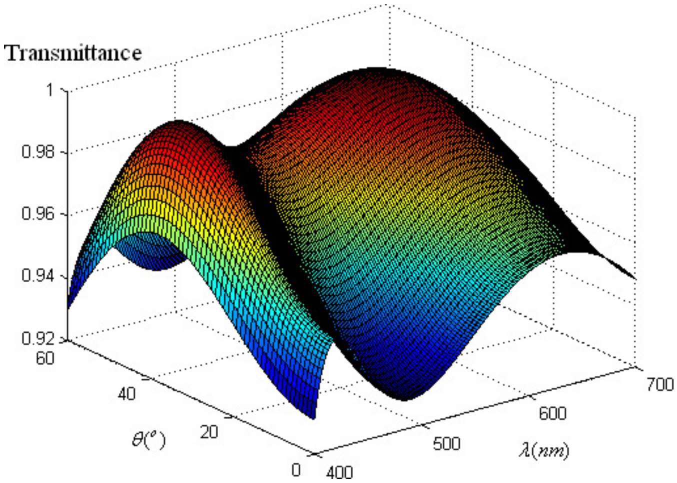

FIGURE 4 — Polarization conversion efficiency versus wavelength and incident angle based on the 2 × 2 extended Jones Matrix method.

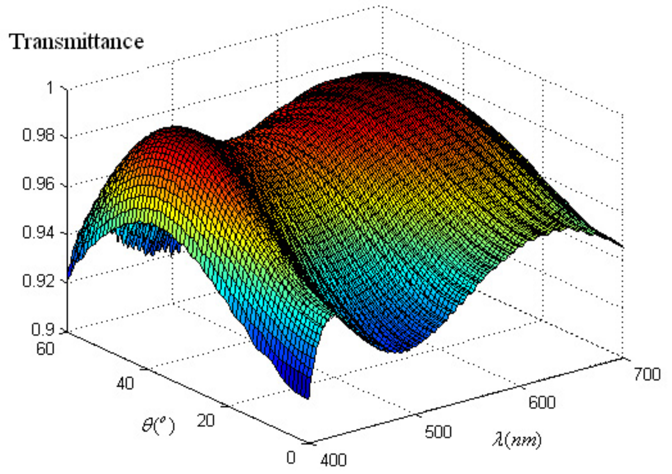

FIGURE 5 — Polarization conversion efficiency versus wavelength and incident angle based on the 4 × 4 method.

only. A local conjugate gradient optimization algorithm together with the Jones matrix method (normal incidence only) was enough to obtain good results. Although the AR coating is not really necessary in the transmissive device design, it is necessary in the reflective device design presented here. In our work, we found that in the design stage we can use the extended Jones matrix method with an ideal AR coating. After that we designed a broadband and wide-view AR coating and confirmed our design using the 4 × 4 matrix method. This is much more efficient than using the 4 × 4 matrix method in the genetic algorithm in the design because the AR coating design does not need to be included in the genetic algorithm search and the 2 × 2 method is usually much faster than the 4 × 4 method.

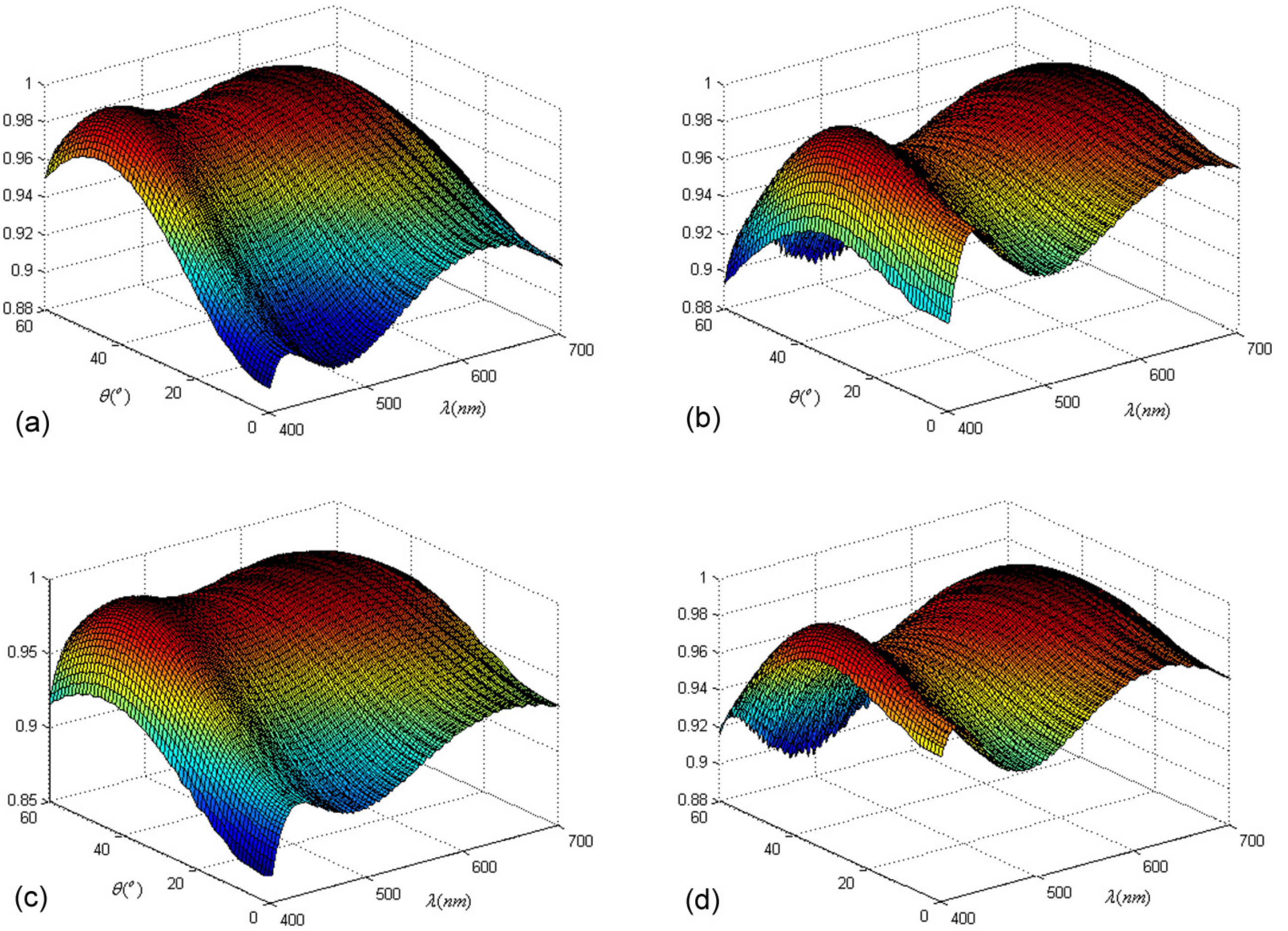

FIGURE 6 — Polarization conversion efficiency (*d*Δ*n*) of the films deviating from their optimal values. In (a) and (b), the *d*Δ*n* of TN film deviates ±5% from its optimal value, respectively. In (c) and (d), the *d*Δ*n* of uniaxial film deviates ±5% from its optimal value, respectively.

4 Simulation results

After global optimization through GA, we can effectively design a broadband wide-incident-angle reflective polarization converter. By running the algorithm developed many times, we can obtain several design results. For the structure given in Fig. 1, we choose $\beta = 86.06°$, $\phi = -31.78°$, $d = 2.74\ \mu m$, $p = 9.81\ \mu m$, and $\alpha = 6.72°$. The AR coating layer we designed is comprised of three layers of isotropic materials, with the refractive indexes (from bottom to top as shown in Fig. 3) of 1.0478, 1.2144, and 1.421, and thickness of 138.22, 115, and 95.69 nm.

Figure 4 shows the normalized TE transmittance (the ratio of the TE component in the reflected light to the incident TM light) as the wavelength varies from 400 to 700 nm, and the incident angle from 0 to 60°. And Fig. 5 shows the results validated by the 4×4 matrix method. The conversion efficiency from TM polarized light to TE polarized light is very high over the entire visible wavelength and wide incident angle, with a maximum 99.77%, minimum 91.33%, and average 96.72%. We find excellent agreement between the 2×2 and 4×4 matrix methods, but the 2×2 matrix method is much faster than 4×4 in global optimization.

We also studied the design tolerance of this device. Figure 6 shows the conversion efficiency when $d\Delta n$ of the TN film [Figs. 6(a) and 6(b)] or the uniaxial film [Figs. 6(c) and 6(d)] deviates ±5% from their optimal values. Even with such a large deviation, the conversion efficiency still remains high, above 85% over 60° incident angle and over the entire visible spectrum. Thus, our design is not very sensitive to fabrication error.

Our design requires a twisted polymer film with an unusual twist angle, which is $\phi \sim -32°$. Fortunately, twisted-liquid-crystal polymer films have been developed as phase compensator for improving the contrast ratio of super-twisted-nematic liquid-crystal displays.[15] On the other hand, the A-plates, including positive and negative birefringence,[16] are fairly easy to fabricate using stretched polymers. Therefore, our design is feasible from material viewpoint.

5 Conclusion

We have successfully designed a broadband wide-incident-angle reflective polarization converter by using a genetic-algorithm-based global optimization approach together with improved extended Jones matrix method simulation. The designed polarization converter has a simple structure consisting of a TN LC film, a uniaxial film, and a reflector. Our design can reach maximum 99.7%, minimum 91.3%, and average 96.7% conversion efficiency for the entire visible spectrum for incident angles from 0 to 60°. The design is verified by the 4×4 matrix method. It is expected that such a broadband reflective polarization converter is particularly useful for enhancing the light efficiency of LCDs.

Acknowledgment

The authors are indebted to Chi-Mei Optoelectronics (Taiwan) for the financial support.

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