

A Method of Controlling the Diffusing Reflector Properties for Reflective Displays

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Abstract

The performance of dichroic sponge polymer dispersed liquid crystals (D-SPDLC) can be improved further by modifying the TFT diffusing reflector using a TiO_2 layer. A metal-like glare was suppressed, and a wider viewing angle than previously reported was achieved. The display showed above newspaper-standard reflectivity and contrast ratio.

1. Introduction

A polymer dispersed liquid crystal cell consists of a thin film sandwiched between transparent electrodes [1, 2]. Such films are composed of a polymer matrix within which small droplets of a liquid crystal (LC) are dispersed. PDLC films usually possess a transparent on-state and a scattering off-state. By doping PDLC with dichroic dyes, the films then exhibit an absorbing off-state and a transparent on-state [1]. Such films are known as dye-doped PDLCs (D-PDLC), dichroic PDLCs or Guest-Host PDLCs. D-PDLCs have the potential to outperform conventional reflective-type twisted nematic LC displays because they:

- 1) have no polarisers, leading to increased reflectivity and viewing angle.
- 2) have greater mechanical stability, allowing for flexible and large area displays.

Furthermore, D-PDLCs outperform conventional dye-doped LCs (D-LC) because the dye absorption is greatly increased due to the optical scattering effect of D-PDLCs; the optical path length in a PDLC is two to three times longer than in a D-LC [3]. This increased path length is due to light scattering caused by a refractive index mismatch between the LC and the polymer matrix [4]. Moreover, the matrix also randomly perturbs the orientation of LC and dye mixture, enhancing the effect of the dye, thus eliminating the need for polarisers.

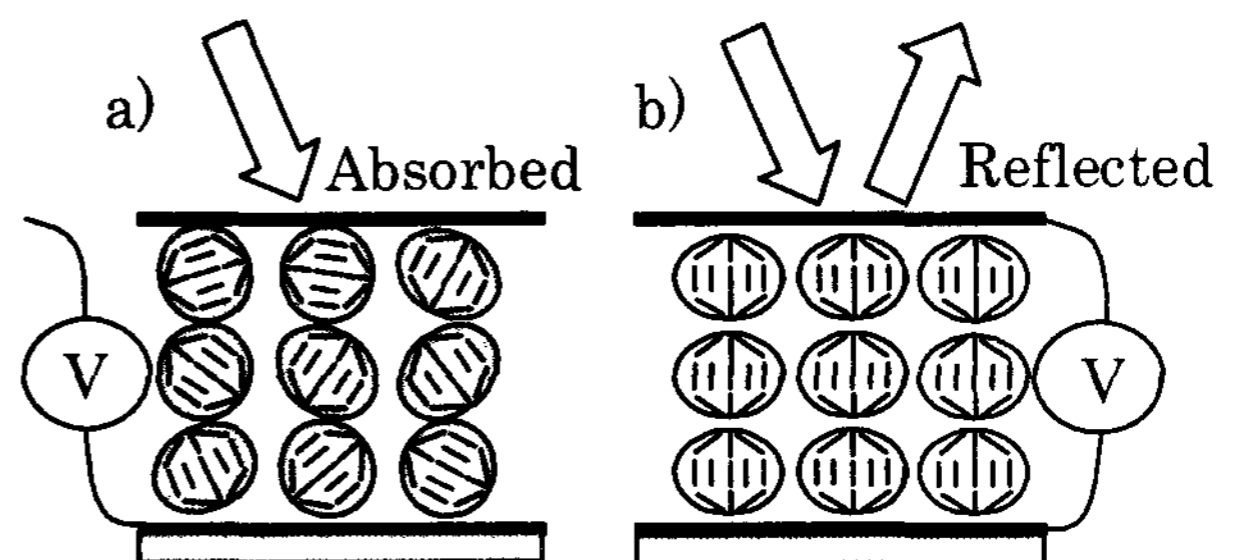


Figure 1 PDLC in the off-state (a) and on-state (b).

Schematic diagrams of a PDLC in the off-state (a) and on-state (b) are shown in Figure 1. The lines in the LC droplets represent the alignment of the LC directors. In the off-state, the film appears both scattering (if there is a refractive index mismatch between the LC and the polymer matrix) and coloured (due to light absorption by the dichroic dye). In the on-state, a field is applied and the directors of the droplets align with the field. The film becomes transparent (if the ordinary refractive index of the LC is similar to that of the matrix) and colourless (if the dye aligns parallel to the electric field).

There are several ways to prepare PDLCs [2], the most common way is the photo-induced phase separation (PIPS) method. In this method irradiating the mixture with UV light induces a phase separation of the LC/pre-polymer mixture. The result is the formation of LC droplets in a polymer matrix. This method is also extensively used to prepare D-PDLC films. However, conventional D-PDLCs suffer from low contrast ratio and low on-state reflectivity, because of:

- 1) degradation of dye/LC during fabrication,
- 2) dye interfering with the cure process,
- 3) trapping of dye/LC in the polymer matrix – making them unresponsive to the electric field.

In our previous work [5, 6], we have developed a very

simple and easy processing method to overcome problems associated with the UV curing process. Such displays exhibit favourable properties such as reflectivity of 98% and contrast ratio (CR) of 8.

Despite this high performance, there was a significant viewing angle dependency; this is largely due to a diffusing reflector used for the conventional TFT [7, 8]. Such a reflector was employed in order to maximize the use of surrounding light using metal electrode with micro-reflective structure. Conventionally, the diffusion property can be controlled by modifying the shape, height and size of the protuberances on such a reflector; but such changes require facilities, time and financial investment.

The disadvantages, shortcomings or requirements of the state of the art are:

- 1) There is a metal-like specula glare from the diffusing reflector due to the interference of the reflected light. In order to prevent this glare, the location of the protuberances needs to be randomly arranged.
- 2) The diffusing property of the reflector designed for TFT application is limited, i.e. the viewing angle of the display is too narrow. In order to modify the diffusing property, the shape and size of the micro-electrode structure needs to be modified at considerable expense.

Researchers are trying to solve the above shortcomings by simulating the diffusing property given by height/size/location of protuberances. If the micro-electrode structure is to be made by a stamping method, then the stamp must be redesigned if the diffusing property is to be changed. If the micro-electrode structure was originally made by photolithography method, then the lithography mask and/or lamp must be redesigned. Thus, the optimisation of protuberances requires much investment in time, money & facilities, and it is not easy to rearrange protuberances completely at random locations over an area.

This report presents an alternative approach to (1) suppression of the glare and (2) control the diffusion property of the reflector, by adding a simple fabrication of a scattering layer on top of the diffusing reflector. The diffusing layer made by TiO₂ particles is thin enough, so that the influence of the layer to the driving voltage of the liquid crystal cell is minimized. Optimizing the TiO₂ particle size may further minimize the layer thickness.

2. TiO₂ Diffusing Layer Preparation

TiO₂ layer was firstly prepared by means of thermal hydrolysis [9]. The solution consists of 10 wt% 10nm TiO₂ nano-particles in 1-propanol, ethanol and water).

In order to obtain a TiO₂-coated reflector with different scattering properties, the TiO₂ solution was doctor bladed at different thickness on a TFT reflector with an existing polyimide blocking layer. Then the 1-propanol, ethanol and water solvents were evaporated at room temperature in a vacuum oven. The layer appears whiter as the layer becomes thicker; because the amount of surface scattering increases with the layer thickness. For thin layers, the TiO₂ did not appear white. Instead, it gave coloured films due to the interference of light. For thicker layers, the TiO₂ did not adhere well to the substrate. Optical microscopy revealed that in some areas the TiO₂ was peeling off, leading to the inhomogeneous appearance.

Figure 2 shows that - even at a viewing angle of 45 degrees- the TiO₂ layers stay whiter than the reflector alone. This indicates that, compared to the ordinary diffusing reflector, the TFT display coated with diffusing layer should have less of a viewing angle dependency on its brightness and contrast ratio. Furthermore, the metal-like specula glare that can be seen on the ordinary reflector was suppressed.

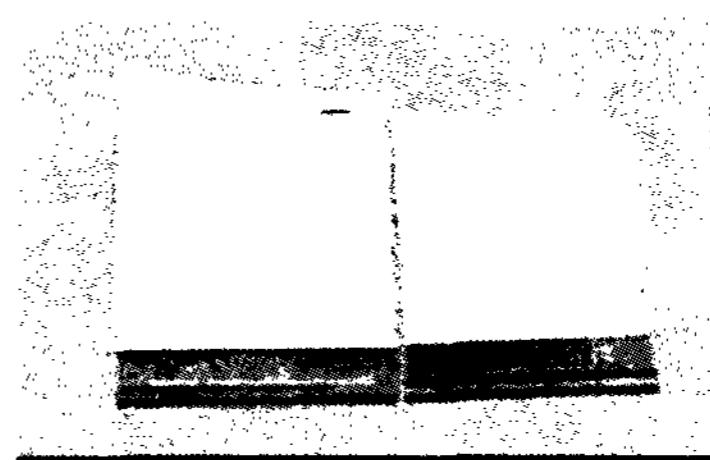


Figure 2 Viewed 45 degrees off from surface normal. Original TFT reflector (right) and one coated with TiO₂ layer (left).

The thickness of the resulting layers was measured by a surface profiler (Tencor P-10) and its dependency with the initial doctor-bladed height was plotted (Figure 3). As expected, the result shows that there is a linear relationship between the two, with the equation $y=0.0265x$ where x is the initial doctor-bladed TiO₂ film thickness and y is the final film thickness in microns. Thin film optical interference was observed when the final film thickness was below 1.2 μ m, and the flakes were observed when the final film thickness was above 4.2 μ m. Hence, the film that is both homogeneously uniform and mechanically stable has a thickness of between 1.2 to 4.2 μ m. This is thin enough

to be used inside a D-SPDLC cell, where the cell gap size is normally 8-15 μm .

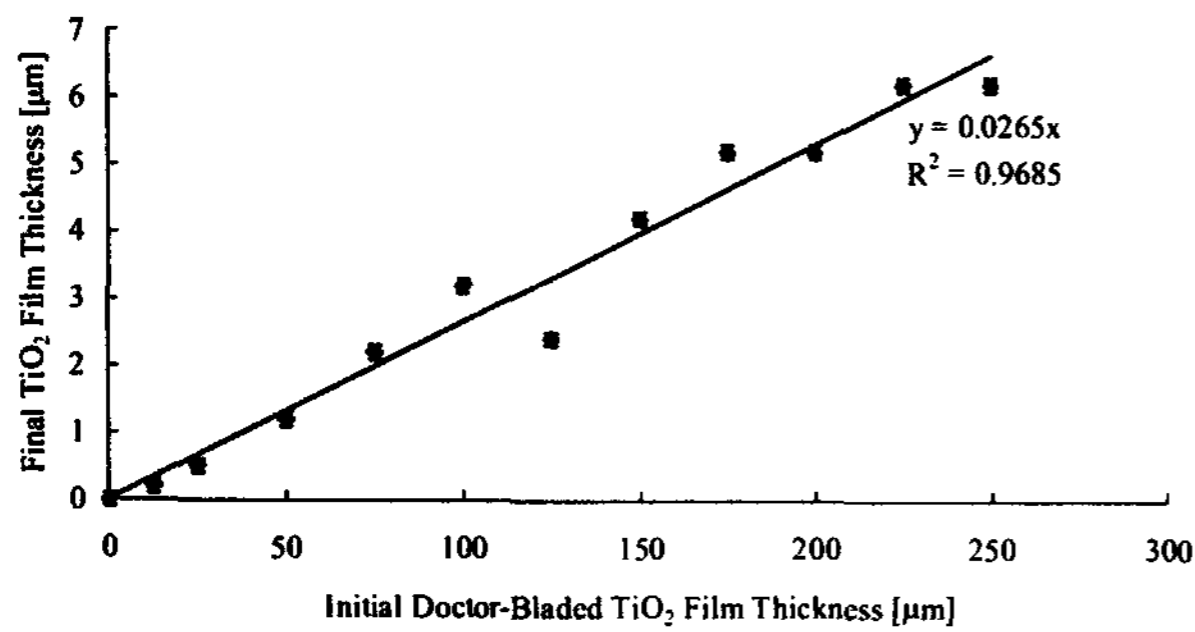


Figure 3. Relation between initial doctor-bladed TiO₂ film thickness and resulting film thickness

3. Angular Dependency of TiO₂ Coated Reflectors Reflectivity

Firstly, the angular dependency of the TiO₂ coated reflector reflectivities were measured using an LCD evaluation system "Photal Otsuka Electronics LCD-700". The detector was set at 0° (surface normal) while the incident parallel white light was moved from $\theta = 15^\circ$ to 70°. The normalization of 99% was taken using diffusing white standard (Labsphere SRS 99-020) when the detector was at 0° and the incident light was at 30°.

Figure 4 shows that the reflectivity peak drops and broadens with increasing TiO₂ thickness. Among those tested, 2.2 μm thickness showed the highest and broadest reflectivity value at 30 degrees. The 2.2 μm TiO₂ layer was uniformly glare-free and had no flakes.

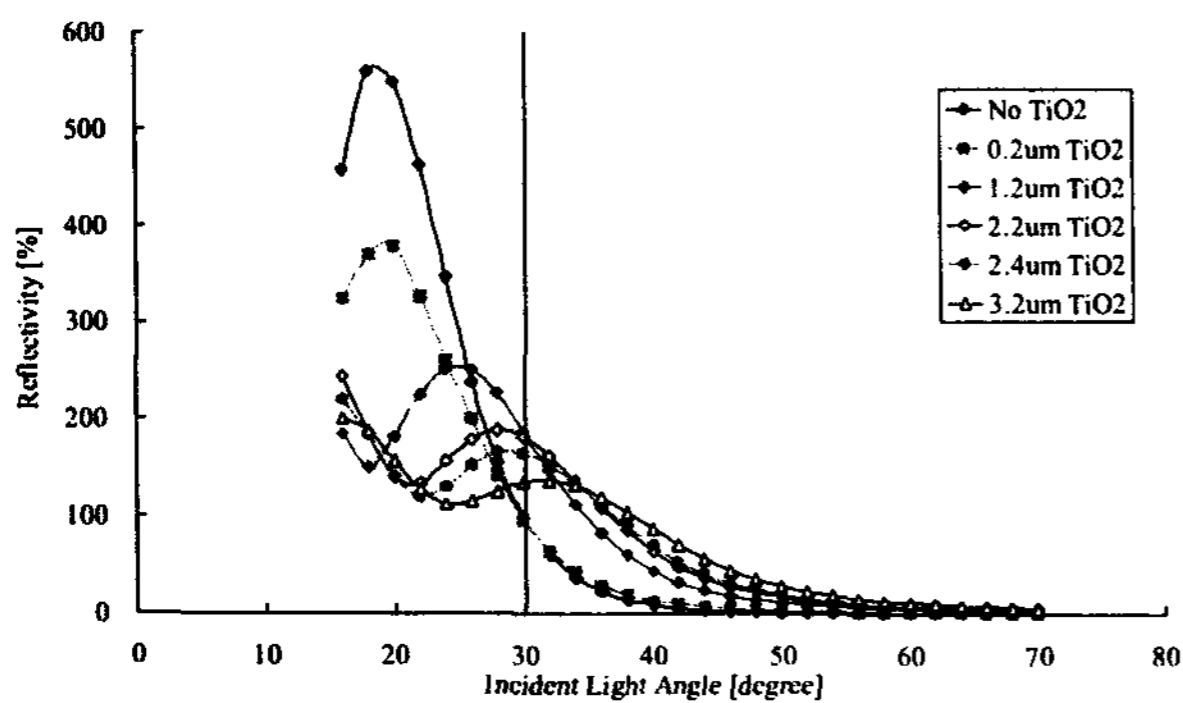


Figure 4 Reflectivity profile of TiO₂ coated reflector

4. Fabrication of Dichroic Sponge PDLC (D-SPDLC)

For the fabrication of D-PDLC, we follow the previously reported recipe [6]. TL213 LC (Merck) and PN393 UV-curable polymer (FFL Funktionsfluid) were used to make the initial PDLC. TL213 is a nematic LC mixture suitable for an active matrix display, and it contains fluorinated and chlorinated aromatic groups [10]. TL213 has an extraordinary refractive index (n_e) of 1.77, an ordinary refractive index (n_o) of 1.53, $\Delta n (=n_e - n_o)$ of 0.24 (589nm at 20°C), and a dielectric anisotropy ($\Delta\epsilon$) of 5.7. PN393 is a blend of 2-ethyl hexyl acrylate monomer and trimethylol propane tri-acrylate cross-linker [11] with a refractive index of 1.47, and it is cured by UV light of wavelengths between 350-360nm.

Firstly, 78.9 wt% TL213 LC and 21.1 wt% PN393 pre-polymer were mixed together with small amount of 8 μm spacers. Within 6 hours of mixing, the solution was sandwiched between two ITO coated glass substrates (no alignment, E.H.C Japan). The cells were irradiated by UV light (360 nm, Spectroline, Model EN-180L/F, 230V, 50Hz, 0.17A) from a distance of 14 mm for 20 minutes at a room temperature of 23°C. As the curing of the polymer progressed, the LC became insoluble in the polymer. This phase separation process leads to the formation of a PDLC film.

Then the 78.7% PDLC cells were opened, and the LC was fully dissolved out of the polymer matrix by washing with methanol. After completely flushing out the LC, the residual solvent was removed from the polymer matrix by placing the cell under vacuum in an oven at 80°C for 3 hours. The end result was an open porosity sponge consisting of a polymer matrix with air cavities (voids). Then, by re-bonding the opened cells together, a glass sandwich cell with the porous polymer matrix of voids was created. Such a cell with a sponge-like texture is referred to as a "Sponge PDLC" (SPDLC).

The empty SPDLC cell is refilled with a 3 wt% B4 doped LC by capillary force. The LC used for the refilling was TL203, which is different from the initial TL213 LC. TL203 is a nematic LC mixture with nematic to isotropic temperature (T_{NI}) of 77°C, with an n_e of 1.73, an n_o of 1.53, Δn of 0.20 (589 nm at 20°C), and a $\Delta\epsilon$ of 11. The dye used was Black-4 (B4) from Mitsubishi Chemical Japan, which consists of six different azo and anthraquinone dyes mixed together. The dichroic PDLCs made using the new fabrication

technique are named "dye-doped Sponge PDLC" (D-SPDLC).

After the refilling, the cell was heated to 110°C for 20 seconds and left until it cooled to room temperature. This annealing process helps to reduce flow alignment defects in the LC introduced during the filling.

5. Angular Dependency of D-SPDLC Reflectivity & Contrast Ratio on TiO₂ coated Reflectors

The D-SPDLC cell was placed on various TiO₂ coated reflectors, and their on/off-state reflectivities (R) were measured (Figure 5); from these measurements their contrast ratio (CR=on-state reflectivity/off-state reflectivity) was calculated (Figure 6).

As expected from Figure 4, reflectivity peak drops and broadens as the TiO₂ thickness increases; 2.2µm TiO₂ (R=64.3%, CR=5.8 at 30°) is favourable in terms of reflectivity, while 3.2µm (R=52.3%, CR=5.4 at 30°) is favoured in terms of the broad viewing angle of its contrast ratio. The D-SPDLC was switched on by applying an AC 1kHz square wave 10Vp-p. The values are expected to be further improved by using more scattering PDLC.

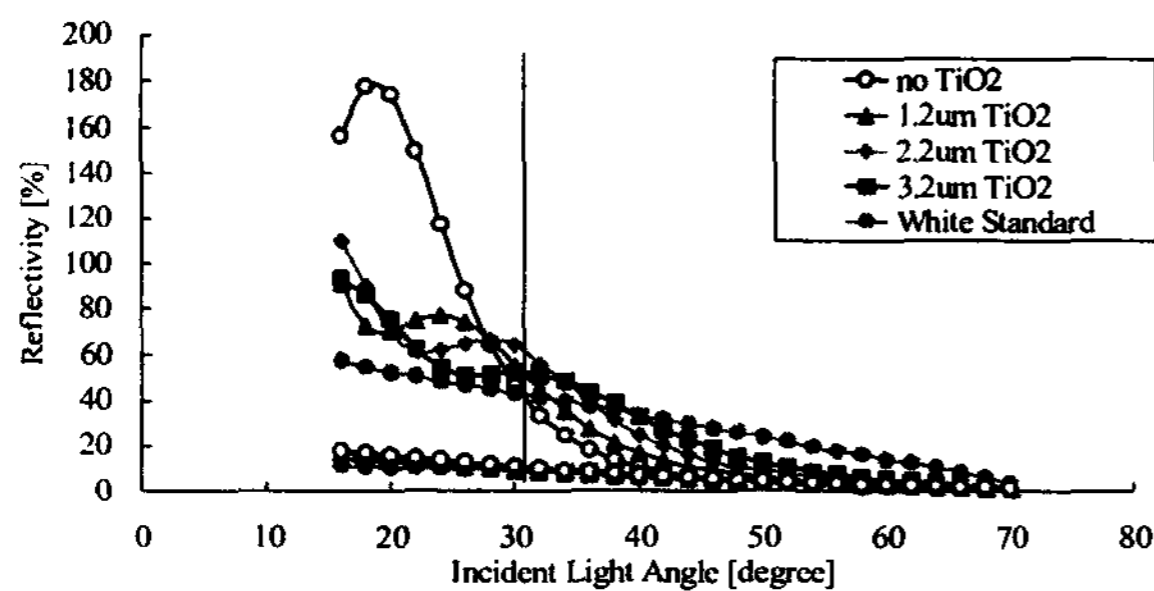


Figure 5 Reflectivity of D-SPDLC on various TiO₂ coated reflectors

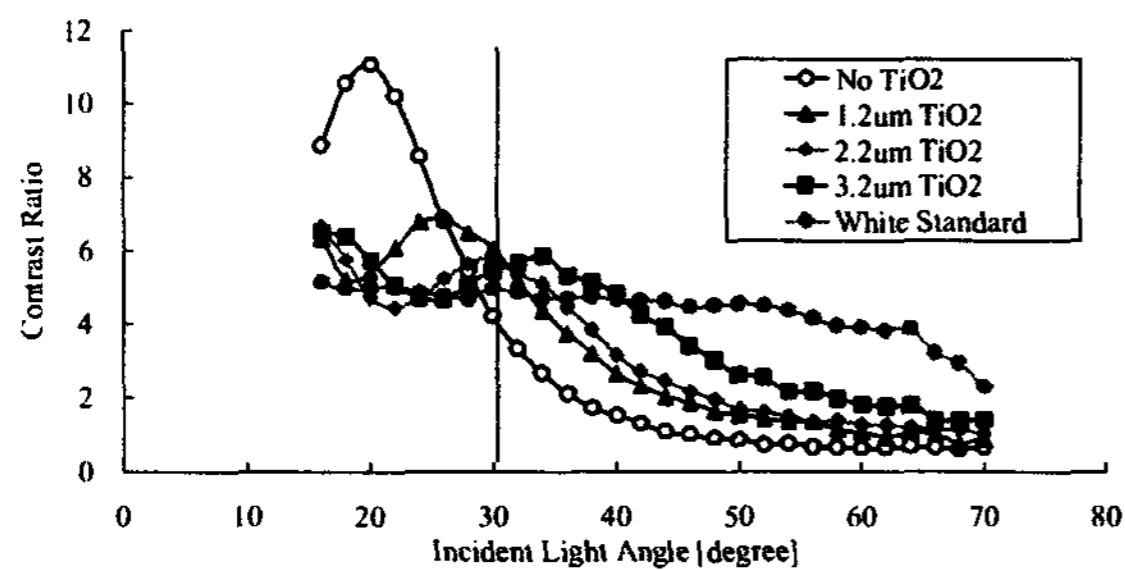


Figure 6 Contrast ratio of D-SPDLC on various TiO₂ coated reflectors

6. Conclusion

By adding a TiO₂ nano-particle scattering layer on top of the diffusing reflector, we showed that we can reduce the specular glare and control the amount and nature of optical diffusion in order to increase the viewing angle, while still keeping the necessary reflectance. The electro-optical properties of the D-SPDLC were improved; thus a reflectivity of 64.3% and a contrast ratio of 5.8 with a wide viewing angle can be achieved using 2.2µm TiO₂ layer.

The main advantage of this method is that it allows one to modify and/or control the diffusing property of the reflector without modifying the protuberances themselves. Also, the diffusing layer created with the TiO₂ particles is thin enough so that the influence of this additional layer on the driving voltage of the liquid crystal cell is minimized. There is further scope to make the layer thickness even thinner by optimizing the TiO₂ nano-particle size.

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