Contrast Ratio Improvement of Optically Switchable Transparent Liquid Crystal Display

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ABSTRACT

We combined a photochromic film with an optically switchable transparent display. The display consists of a PNLC and light sources. Post ultraviolet irradiation, the PNLC and photochromic films changed from the initial transparent state to the screen and dimming states, respectively. Photochromic films block background light and improve contrast ratio.

1 Introduction

Transparent displays have attracted significant attention in recent years. They are applied to store signage windows, automotive windows, and head-mounted displays. Currently, common transparent display technologies, including active matrix organic light-emitting diodes (OLEDs)[1], waveguide displays, and thin-film transistor (TFT) liquid crystal displays (LCDs)[2], have drawbacks such as low transparency and inflexibility. We have developed a projection-type optically switchable transparent LCD comprising a photoresponsive polymer network liquid crystal (PNLC) and light sources.[3] It is expected to exhibit high transparency and good flexibility.

The image quality of a transparent display varies depending on its surrounding environment. If the background brightness is stronger than the luminous intensity of the displayed images, the background light interferes with the images on the display, resulting in low image quality and low contrast ratio. Light shutters such as dichroic dye-doped guest-host liquid crystals (LCs), polymer-dispersed LCs (PDLCs), and electrochromic materials are added to waveguide displays[4], OLEDs[5], and head-mounted displays[6] to block background light and improve image quality. However, because of the need for control systems of light shutters such as TFTs, the transmittance of the displays decreases, resulting in low visibility of background information.

We introduced a photochromic-film light shutter for optically switchable transparent LCDs as it does not require other control systems, such as TFTs; thus, the visibility of the background information does not decrease. We laminated a photochromic-film light shutter on the backside of an optically switchable PNLC. Post ultraviolet (UV) (365 nm)-light irradiation, the PNLC is converted from a transparent state to a light-scattering screen state. The photochromic film reacts with the UV light transmitted through the PNLC, changing from a transparent state to a dimming state. In the dimming state, the photochromic film blocks the background light.

In this study, we verified whether the same UV light source can control PNLC and photochromic films and whether the contrast ratio of optically switchable transparent displays can be improved using a photochromic-film light shutter.

2 Principle of optical switching transparent LCD with photochromic-film light shutter

2.1 System layout

Figure 1 shows the system layout of an optically switchable transparent LCD combined with a photochromic film. The system comprises an optically switchable PNLC, photochromic film, visible light projector, UV-light light-emitting diode (LED), and blue-light LED. In the initial transparent state, the PNLC and photochromic films are transparent. When the UV light is irradiated to the display, the PNLC in the irradiated area is converted from a transparent state to an opaque state. Furthermore, the UV light transmitted through the PNLC causes the photochromic film to be dimming. After UV light irradiation, the visible-light projector projects images onto the screen area. Subsequently, irradiation with the blue light returns the PNLC and the photochromic film changes to its initial transparent state.

2.2 Structure of optically switchable PNLC and photochromic film shutter

Figure 2 shows a schematic of an optically switchable transparent LCD and photochromic film. The glass substrates were coated with an ITO electrode and a vertically aligned polyimide (PI) film. Chiral azobenzene and non-photochromic chiral compounds were doped into the PNLC. The polymer network consisted of reactive mesogens, which stabilized the vertical alignment of LCs. Photochromic materials (diarylethene derivatives) were dispersed in a polymethylmethacrylate (PMMA) film and laminated on the photoresponsive PNLC.

In the initial transparent state, the helical twisting powers (HTPs) of transchiral azobenzene and non-photochromic chiral compounds are equal; thus, the LCs are in the compensated nematic phase and show high transparency[7,8]. Diarylethene derivatives in photochromic films are also transparent (open-ring state).

On UV light irradiation, the chiral azobenzene transforms from the trans-state to the cis state, and the balance of the HTP between the non-photochromic chiral compound and azobenzene is disrupted. The compensated nematic phase transforms into the cholesteric phase. Consequently, the orientations of the LCs are disordered, and a light-scattering screen appears. A UV light transmitted through PNLC transforms diarylethene derivatives in a photochromic film from an open-ring state to a closed-ring state.

Diarylethene derivatives in the closed-ring state absorb visible light. They block the background light and act as light shutters. When the screen was irradiated with blue light, the chiral azobenzene in PNLC and diarylethene derivatives in the photochromic films returned to their initial trans-state and open-ring state, respectively. The light-scattering screen disappeared.

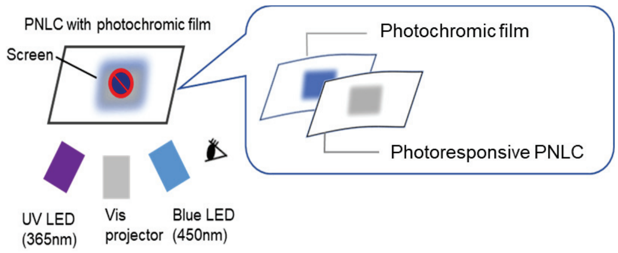

Fig. 1 System layout of optically switchable transparent LCD combined with photochromic film.

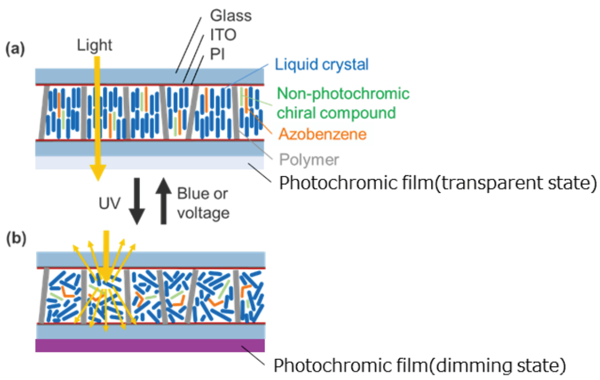

Fig. 2 Schematic of optically switchable transparent PNLC and photochromic film in (a) transparent state and (b) screen state.

3 Experimental

Figure 3 shows the materials used in this study, and Table 1 lists the compositions of the liquid crystal mixtures. We used a positive nematic liquid crystal, Sb-826010 (Tsukasa Research Labs, Δn=0.26), two reactive mesogens,4,4'-bis(6-(acryloyloxy)-hexyloxy)biphenyl (RM-A), 4,4'-bis(4-(6-(acryloyloxy)-hexyloxy)benzoate)-1,1'-biphenylene (RM-B) (Tokyo Chemical Industry Co., Ltd.), and Iragcure819 (Ciba Specialty Chemicals Inc.) as photoinitiators. Chiral azobenzene and non-photochromic chiral compounds were synthesized and utilized.

We fabricated PNLC as follows. We coated a vertically aligned PI film on an ITO glass substrate (EHC). Empty glass cells, each with a cell gap of 10 μm, were prepared by assembling them. An LC mixture was injected into the empty cells via capillarity on a hot plate at 100 degrees celsius, equal to the liquid crystal clearing point.

LC mixtures in the cell were exposed to blue light from an LED (λ_{max} = 420 nm) under voltage application (50 V, 50 Hz) at 35 degrees celsius for 10 min. The blue-light intensity was set at 7 mW/cm^2.

Two diarylethene derivatives (DAE18 and DAE12 [Yamada Chemical]) were mixed with a PMMA solution (Yamada Chemical). The concentration of the diarylethene derivatives was 1.8 wt%. A photochromic film was prepared by drop-casting a PMMA solution onto the backside of the PNLC.

The optical properties of the fabricated PNLC and photochromic films were evaluated by measuring the transmittance spectrum and haze values before and after UV irradiation. Transmittance spectra were measured using a color difference meter (CM3600 Konica Minolta, Inc). Each haze value was measured using a haze meter (HM-65 W; Murakami Color Research Laboratory).

The contrast ratio of the display was calculated by determining the luminance values for the PNLC with and without white image projection using a luminance meter. Images were projected using a projector (MW612; BenQ). The PNLC was illuminated with white light (10000 lx) from the background side during the contrast ratio measurements. While determining the contrast ratio, we removed the photochromic films from the PNLC and irradiated the UV light separately. The PNLC was irradiated with UV light (λ = 365 nm) for 60 seconds and was varied sufficiently to the screen state. The UV light intensity was set to 20 mW/cm^2. The transmittance of the photochromic film was changed by varying the UV irradiation time. We then laminated the photochromic film on the PNLC again and calculated its contrast ratio.

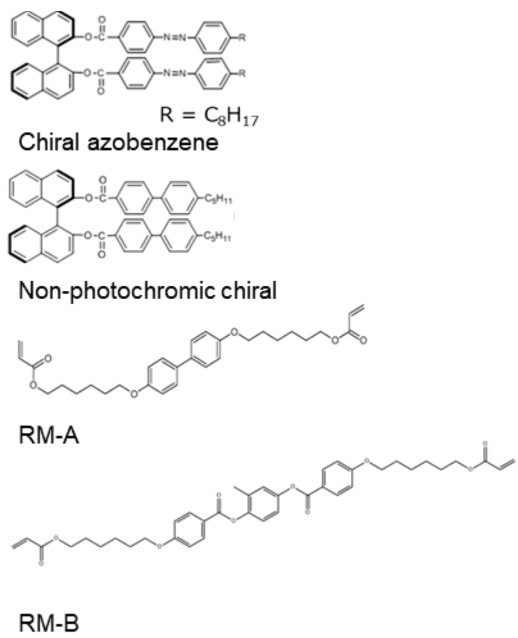

Fig. 3 Molecular structures of materials

Table 1. LC mixture components (wt%)

LC	Chiral azobenzene	Non-photochromic chiral	RM-A	RM-B	Photoinitiator
86.5	5.1	2.9	3.3	1.7	0.5

4 Results and discussion

Figure 4 shows the total transmittance of the photochromic films before and after sufficient UV irradiation (λ_{max} = 365 nm) at 20 mW/cm^2 for 60 s. Total transmittance is the sum of specular transmittance and diffuse transmittance. Before UV irradiation, the average transmittance exceeded 80% throughout the visible region. After UV irradiation, the diarylethene derivatives in the photochromic films were sufficiently converted to the closed-ring state, and the transmittance in the visible region decreased. The transmittance decreased to almost 0% within the wavelength between 500 and 600 nm.

Table 2 lists the optical properties, and Figure 5 shows the total transmittance of the PNLC combined with the photochromic films. The transmittance of the PNLC is also shown in Figure 5. In the initial transparent state, the photochromic films slightly reduced the transmittance of the PNLC. The average transmittance decreased to 78.8% in the visible region, and the haze value was 2.2%. In the wavelength region below 400 nm, the transmittance decreases owing to the light absorption of azobenzene in PNLC and diarylethene derivatives in the photochromic films. 10% of the irradiated UV light (λ = 365 nm) reached the photochromic films because it transmitted approximately 10% of the UV light. After UV irradiation, the transmittance in the visible region of the PNLC decreased from 21.0% to 6.8%, showing that the PNLC and photochromic films could be controlled by the same UV light. The haze value of PNLC in the screen state was almost unchanged with photochromic film lamination.

Figure 6 shows the variation in the contrast ratio of the display. The contrast ratio is influenced by the transmittance of the photochromic film. The contrast without the photochromic film was approximately 1.6. When the transmittance of the photochromic film was 30%, the contrast ratio of the display increased to 4.8.

Figure 7 shows an optically switchable transparent display combined with a photochromic film. The sample had a size of 10 cm × 10 cm. In the initial transparent state, the sample was as transparent as glass. After UV irradiation, the PNLC changed to a light-scattering state, and a screen appeared in the irradiated area. The photochromic films blocked background light and improved the visibility of the projected image. When the projection was stopped, and blue-light irradiation was applied, the display returned to its initial transparent state.

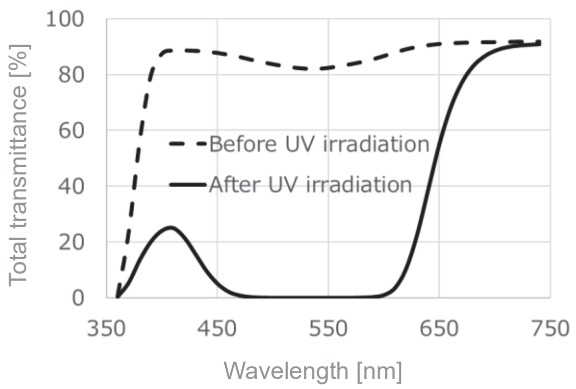

Fig. 4 Transmission spectrum of photochromic films before and after UV irradiation.

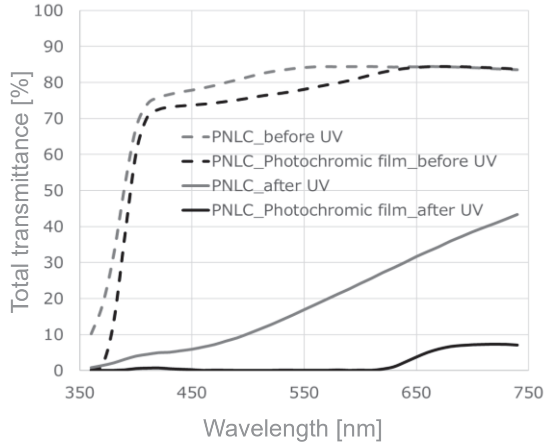

Fig. 5 Transmission spectra of PNLC and PNLC combined with photochromic film.

Table 2. Optical properties

Samplem	Total transmittance / Haze	
	Transparent state	Screen state
PNLC without Photochromic film	81.7% / 1.6%	21.0% / 97.2%
PNLC with Photochtomic film	78.8% / 2.2%	6.8% / 94.6%

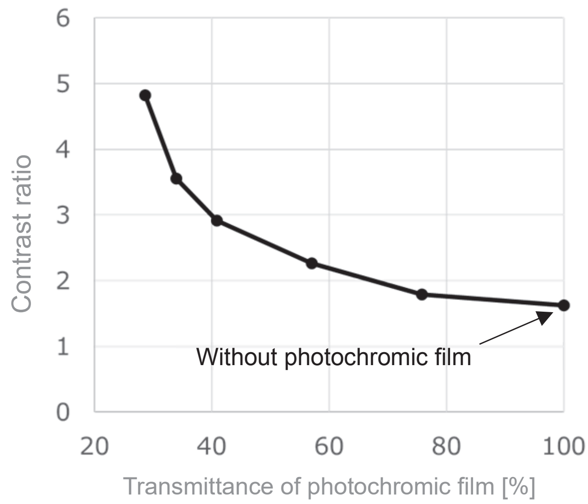

Fig. 6 Relationship between transmittance of photochromic film and contrast ratio of display photochromic film.

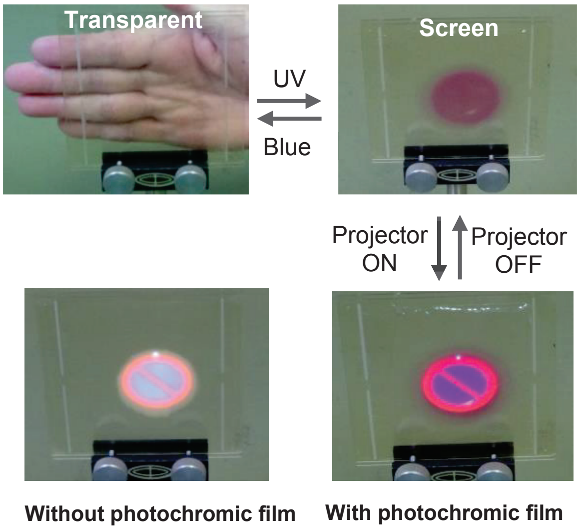

Fig. 7 Photographs of optically switchable transparent LCD of 10 cm x 10 cm sample.

5 Conclusions

We improved the image visibility of the optically switchable projection-type transparent LCD. The display consisted of an optically switchable PNLC, UV and blue LEDs, and projector. PNLC reversibly changes from a transparent state to a light-scattering screen state via light irradiation. We combined PNLC with photochromic films. We achieved high transparency in the transparent state and improved the visibility of the projected image in the screen state.

The transmittance in the visible region of the display in the transparent state was 78.8%, while the display contrast ratio varied with the transmittance of photochromic film. When the transmittance of the photochromic film was 30%, the display contrast ratio was 4.8, whereas the contrast ratio of the PNLC alone was 1.6.

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