1. Introduction

Transparent displays have been extensively studied over the past few years owing to their promising applications in advanced displays, including near-eye displays,[1–3] window displays,[4] and wearable devices. A transparent display is also referred to as a see-through display, which is capable of not only displaying images but also receiving the environmental information behind the display. The most common types of technologies used for transparent displays include liquid crystal (LC) displays,[5–7] organic light-emitting diodes,[8,9] projection type,[10–13] and other types of displays. Despite each type exhibiting its unique strengths and weaknesses, projection-type transparent displays have been increasingly investigated because they are cost effective owing to the absence of complex driving circuits on the screen. Traditional projection displays comprise a projector and projection screen, wherein the projector provides the image information, and the projection screen with an opaque surface delivers this information to the human eye by scattering the light. Unlike traditional projection displays, screens in projection-type transparent displays require a semitransparent surface to obtain light information while displaying the background image.[14–16] Despite extensive progress in semitransparent projection screens, a trade-off exists between display performance and transparency. Additionally, the bright light background may disturb the projected images significantly, resulting in image distortion and a low contrast ratio.

To address this problem, several researchers have attempted to realize active projection screens that can switch between transparent and opaque states. The projected area is in the opaque state where the light information is scattered to the human eye and the background behind the screen is blocked, whereas the non-projected area is in the transparent state to render the image background transparent. To date, several active projection screens based on hydrogels, nanoparticle-doped media, and LCs have been proposed. Yang et al. developed a projection screen composed of cross-linked hydrogels and near-infrared absorption heating films. Here, the light transmittance of the screen can be controlled by a near-infrared laser to achieve a real-time information provision display.[12] Hsu et al. created a convenient transparent display by projecting monochromatic images onto a transparent medium embedded with nanoparticles, which can selectively scatter light in the projected area.[10] He et al. applied polymer-dispersed liquid crystals as active screens in multifocal plane see-through displays, which can scatter light strongly at large oblique angles.[17]

However, although active projection screens successfully reduce the background interference, their opaque state based on light scattering behavior exhibits a low reflectance of 10%.
This requires a brighter image from the projector, thus consuming high amounts of power. Therefore, developing an active projection screen with a large contrast ratio between transparent and opaque states and high optical performance, such as high reflectance and wide viewing angle, is highly desirable; however, it is difficult to be achieved. Recently, an alternative active projection screen that uses optically rewritable cholesteric liquid crystals (CLCs) was proposed. CLCs in the planar state exhibit Bragg reflections with an ideal reflectance of 50\%, thus producing better display images. However, certain challenges are inherent in using CLCs as an active projection screen, including the narrowband and incident-independent reflection and large driving voltage. Therefore, in this study, we fabricated an ultra-broadband reflective diffuser based on polymer-stabilized cholesteric liquid crystals (PSCLCs). Based on this, an active projection screen composed of a PSCLC diffuser and polarization converter is proposed. The ultra-broadband reflection in PSCLCs is realized by employing chiral monomers (CMs), named LC756, which are photo-polymerizable chiral agents. In typical, creating a gradient-pitch helical polymer structure throughout the cell by photo-polymerization is one of the most commonly used methods to broaden the reflection band of CLCs. The formation of a gradient in the helix is mainly determined by the reaction and diffusion rates of reactive monomers in the mixtures as well as the polymerization conditions. Various kinds of reactive monomers, including chiral monomers, nematic monomers, or monomers with different reactive sites per molecule, have been employed to realize PSCLCs with a broad reflection band; however, most broadband PSCLCs exhibit mirror-like reflection rather than the diffusion reflection. The reason why the LC756 CMs were selected as the reactive monomers is that such CMs can generate cobweb-like polymer structures on surfaces and form multi-domain planar states after photo-polymerization. As expected, LC756 CMs after polymerization form a gradient-pitch helical structure with multi-domain planar states, enabling the PSCLC diffuser to diffusely reflect circularly polarized light with the same handedness as that of the helical structure across the entire visible region. Such a PSCLC diffuser with circular polarization selectivity results in two different optical states, namely the transparent and reflective states, based on the handedness of the circularly polarized incident light. Therefore, an active projection screen can be realized by adding a polarization converter, which can switch the handedness of the circularly polarized light to a passive PSCLC diffuser.

Figure 1 depicts the schematic of the proposed projection-type transparent display system, which comprises a projector to produce the projected images, an active projection screen composed of a pixelated polarization converter, and a passive PSCLC diffuser. In the projected area, the front polarization converter ensures that the incident light from the projector is circularly polarized with the same handedness as that of the helical structure in the PSCLC diffuser. Therefore, the PSCLC diffuser remains in the reflective state, which delivers display information while blocking the background light. In the non-projected area, the front polarization modulator (PM) produces opposite-handed circularly polarized light, and the PSCLC diffuser remains in the transparent state where the projected and background images pass through the projection screen. The PSCLC diffuser is optimized because the display quality of the projection-type transparent display strongly relies on the optical performance of the PSCLC diffuser. Additionally, a proof of concept for the projection-type transparent display is demonstrated in the subsequent sections.

2. Experimental Section

We prepared the CLC mixture composed of 94.5\% nematic liquid crystal host (E7, HCCH) with a positive dielectric anisotropy ($n_e = 1.7429$, $n_o = 1.5198$), 4.5\% chiral monomer (LC756, BASF), 1\% photoinitiator (Irg651, HCCH), and additional 0.3\% chiral dopant (R5011, HCCH). The handedness of the chiral dopant R5011 is identical to that of LC756; it was added to the mixture to ensure that the initial center wavelength ($\lambda_0$) of the reflection band in the CLC mixture before polymerization was located at 360 nm. The mixture was stirred in the isotropic phase for 4 h to ensure homogeneous mixing. These PSCLC diffusers were fabricated as follows. Initially, the CLC mixture was injected into the empty cells, comprising two pieces of glass substrates with rubbed homogeneous alignment layers. Consequently, these samples exhibited Grandjean textures at 25°C. The thicknesses of the LC layer in cells were controlled by plastic spacers of different sizes of 12, 25, and 38 μm. Subsequently, these samples were placed on a temperature controller (INSTEC, mK2000) that provides the different polymerization temperatures of 15, 25, 40, and 50°C; they underwent in situ photo-polymerization via unpolarized UV light (Brighttek, BK Spot Cure-100) with various intensities of 1000, 100, 1, and 0.1 mW cm$^{-2}$ for 20 min. Finally, broadband PSCLC diffusers were formed. To evaluate the optical characteristics of these PSCLC diffusers, a fiber-optic spectrometer (USB4000, Ocean Optics) was used to collect the spectra, and haze measurements were performed using a haze meter (NDH 7000, Nippon Denshoku). Spectralon, which exhibits a perfect Lambertian surface (Edmund Optics) independent of the viewing angle, and a traditional commercial projection screen were used as a reference standard. Additionally, for comparison, we fabricated another broadband PSCLC sample based on the ion-dragging effect, which produced a mirror-like reflection of white light.

3. Results and Discussion

3.1. Broadband PSCLC Fabrication and Its Optical Performance

To gain insight into the broadening behavior of the PSCLC diffuser, a 12 μm thick PSCLC cell was examined. The cell was exposed to UV light with a light intensity of 0.1 mW cm$^{-2}$ at room temperature for the polymerization process. As depicted in Figure 2a, the CLCs exhibited a uniform helical structure with a single pitch before polymerization, and a broad reflection band with a bandwidth greater than 400 nm was formed after curing. The underlying mechanism can be attributed to the CMs that form a solid cholesteric polymer network with a pitch gradient through the cell after UV irradiation. The UV absorption in CMs leads to a nonuniform distribution of UV intensity, and CMs are consumed from the top of the UV lamp to the bottom through the cell. Therefore, the UV gradient within the cell...
allows CLCs to generate a gradient-pitch structure, where the cholesteric helical pitches near the UV lamp with higher irradiation are larger than those with lower irradiation. After polymerization, the reflectance of the central reflection band...
in the 12 μm thick PSCLC cell decreases, and the bandwidth of the reflection band increases from 50 to over 400 nm, as depicted in Figure 2b. To achieve a perfect Bragg reflection in CLCs, a sufficient thickness of greater than 10 pitch lengths is required. Consequently, the decrease in reflectance and flattening of the spectrum reveals that the thickness of 12 μm is not thick enough to reach the ideal reflectance over the entire reflection band. Furthermore, the morphology of the CLC cell was observed under a polarizing optical microscope (POM) with crossed polarizers. We determined that a broadband PSCLC exhibits a multi-domain planar texture rather than a perfect Grandjean texture, as depicted in Figure 2c. Nevertheless, such a multi-domain planar texture maintains perfect circular polarization selectivity, wherein only right-circularly polarized light can be reflected by the PSCLCs. This can be further validated by observing the cell under POM with a circular polarizer in reflection mode, as depicted in Figure 2d,e. When the cell is observed with a left circular polarizer, the multi-domain planar texture disappears, which indicates that left-circularly polarized light passes directly through the CLC structure without any light reflection or scattering. By contrast, the chaotic multi-domain planar texture can be observed under the right circular polarizer, which enables a diffuse reflection for right-circularly polarized light. Therefore, by controlling the polarization state of the incident light, a PSCLC cell exhibits two different optical states, namely the transparent and reflective states. These are the two promising states for active projection screens in projection-type transparent displays. In the reflective state, also referred to as the projection state, the PSCLC cell can exhibit high reflectivity while blocking the background. Additionally, the corresponding multi-domain planar texture enables wide viewing angles, as depicted in Figure 2g. In the transparent state (Figure 2h), the PSCLC cell exhibits a see-through property that allows the image to pass through it.

Unlike the well-planar texture of CLC, which has a mirror-like reflection and narrow viewing angles, the multi-domain planar texture of the broadband PSCLC exhibits diffusion reflection, which results in wide viewing angles that are considered comparable to the traditional projection screen for scattering light. To understand the characteristics of the diffused reflection of the multi-domain planar texture, we measured the intensity of the reflected light at different angles using the experimental setup depicted in Figure 3a. The incident angle of the light source was set to −10°, and the intensities of the reflected light were measured using a fiber-optic spectrometer at angles varying from +10° to +90° in increments of 10°. Apart from the PSCLC cell with the multi-domain planar texture, we measured a metal mirror, a commercial scattering-type projection screen, Spectron, and another PSCLC cell with a uniform planar texture for comparison. Figure 3b illustrates the measured intensities as a function of received angles (viewing angles). As expected, the Spectron with near-perfect Lambertian surfaces and the commercial projection screen exhibit an ultrawide viewing angle of approximately 90°. Furthermore, both metal mirror and PSCLC cell with uniform planar texture provide nearly perfect mirror-like reflection, thus resulting in a narrow viewing angle of less than 10°. The PSCLC cell with the multi-domain planar texture exhibits a smoother reflection under a relatively wider viewing angle of ≈55°.

3.2. Optimization of Optical Performance

After verifying that the broadband PSCLC with multi-domain planar texture is a promising candidate for active projection screens, the optical properties including reflectance and bandwidth of the PSCLC cell were optimized by adjusting the polymerization conditions and thickness of the cell to achieve a high-quality display performance. In general, the optical performance of the PSCLC strongly relies on the distribution of the polymer network. The morphology of the polymer network can be determined by controlling the monomer diffusion rates based on the temperature and UV light–intensity regulation during photo-polymerization. Under UV illumination, the monomer tends to diffuse toward the UV-illuminated side, and suitable monomer diffusion rates enable a large reflection band of the PSCLCs with high reflectance. The optimization process was performed as follows. Initially, 12 μm thick PSCLC cells were fabricated and cured under 0.1 mW cm−2 UV exposure intensity at different temperatures. Figure 4a depicts the reflection spectra. The result indicates that the reflection bandwidth of the cells increases as the temperature increases because of the higher monomer diffusion rate. The main reflection peak redshifts due to the reduction in the concentration of CMs in the LC bulk after polymerization.[24] However, as the temperature increased to 40 °C, a higher reflectance appeared at 750 nm beyond the visible region. Therefore, a temperature of 25 °C is more appropriate in terms of the reflectance within the visible region. Subsequently, 12 μm thick PSCLC cells, which were cured with different UV exposure intensities at a fixed temperature of 25 °C, were measured and compared (Figure 4b). This indicates that the reflection bandwidth of the cells increases with the decreasing curing light intensity. This is because the monomers have sufficient time to diffuse throughout the cell and form a pitch-gradient polymer network at a lower UV light intensity. Thus, the optimum polymerization condition is an exposure intensity of 1 mW cm−2 with a curing temperature of 25 °C. Finally, different thicknesses of the PSCLC cells were considered. Ideally, a highly thick cell supports sufficient helical structures for each pitch and further enhances the reflectance of the reflection band. Figure 4c depicts the reflection spectra of the 12, 25, and 38 μm thick PSCLC cells. As expected, the reflectance increased significantly as the thickness increased. Nevertheless, although the 38 μm thick PSCLC cell exhibited an improved optical behavior in the projected state, the transparency in the transparent state decreased because of the relatively weak anchoring energy and low-ordered alignment of LCs, resulting in light scattering. To examine the transparency of the transparent state in PSCLC cells of different thicknesses, their haze values were measured using a haze meter; here, the incident light was circularly polarized. The experimental results indicate that the thicker cell has a higher haze value, and the haze values of 12, 25, and 38 μm thick PSCLC cells in the transparent state were ≈13.3%, 17.7%, and 22.5%, respectively. Considering the trade-off of reflectance and transparency between projection and transparent states, we concluded that the 25 μm thick PSCLC cell with high reflectance (>35% over the entire visible spectrum), wide viewing angle (≈60°) in the projection state, and high transparency (haze <20%) in the transparent state is the most suitable optical reflector as a projection screen.
3.3. Demonstration of Projection-Type Transparent Display

In the practical application of the projection-type transparent display, the active projection screen comprises a passive PSCLC diffuser that can switch between reflective and transparent states and a PM to control the handedness of the circularly polarized incident light. The PM is composed of a linear polarizer, namely the 90° twisted nematic liquid crystal (90°-TNLC), and a broadband quarter-wave plate (QWP). Driving the TNLCs to modify the handedness of the circularly polarized light enables the active projection screen to operate between the projection and transparent states.

**Figure 5** depicts the operating principle of the proposed active projection screen. In the projection state where the 90°-TNLC is off, the forward incident unpolarized white light (or projection image) becomes right-circularly polarized light after passing through the PM. Subsequently, the right-circularly polarized light is diffusely reflected by the passive PSCLC diffuser. Consequently, the reflected right-circularly polarized light passes through the PM again and is received by the observer. Simultaneously, the backward incident unpolarized white light (background light) first encounters the PSCLC diffuser, and the light with right circular polarization is reflected by the PSCLC diffuser. The left-circularly polarized light is transmitted through the PSCLC diffuser and converted into linearly polarized light by the 90°-TNLC and broadband QWP. Finally, the linearly polarized light is absorbed by the linear polarizer. Thus, the projection state reflects the image created by the projector to the observer while simultaneously blocking the background light. In the transparent state, wherein the 90°-TNLC is on, the forward incident unpolarized white light becomes left-circularly polarized light by the PM and passes through the PSCLC diffuser. In this case, no reflection occurs. Furthermore, the backward incident white light with right circular polarization is reflected by the PSCLC diffuser, and the light...
with the opposite-handed circular polarization is transmitted. The transmitted left-circularly polarized light passes through the PM without light absorption. In this case, the observer can distinctly see the background light.

Furthermore, we demonstrated the feasibility of the projection-type transparent display, as depicted in Figure 6a. To demonstrate the concept of the pixelated display, the indium-tin-oxide (ITO) electrode of the 90°-TNLC was spatially...
etched such that only the circular patterned area could be driven. When no voltage is applied, the active projection screen behaves similar to a see-through window, and the image behind the screen can be seen clearly, as depicted in Figure 6b. When a sufficiently large voltage is applied, the area with the ITO electrode operates in the projection state and appears black owing to the perfectly blocked background light, as shown in Figure 6c. When the image is projected onto the screen, the projection area presents a good image display, as depicted in Figure 6d.

Most existing active projection screens can be roughly divided into two categories, scattering-type and reflective-type screens. In general, the scattering-type projection screens exhibit the wide viewing angles but a low reflectance of ≈10%, while the reflective-type screens have the high reflectance but narrow bandwidth and viewing angles. The fabricated active projection screen based on a highly polarization-selective reflective PSCLC diffuser exhibits a high reflectance of >35% in the reflective state, a low haze value of <20% in the transparent state, and a wide viewing angle of ≈60°. In addition, the proposed projection-type transparent display in which the projection state reflects the image to the observer while simultaneously blocking the background light significantly not only improves the background interference but also reduces the optical crosstalk between unprojected and projected regions. Therefore, it has comparative advantages over other projection-type transparent displays in terms of optical properties, driving voltages, and image quality. Nevertheless, given the current limitation of the projectors that must compete with ambient light and the inevitable decrease in display quality under the high background light, restriction of usage scenarios is required for the proposed projection-type transparent display to work properly.

4. Conclusions

In this study, we propose an active projection screen based on a PSCLC diffuser incorporating a PM for projection-type transparent display applications. Owing to the presence of CMs, the PSCLC diffuser exhibits a pitch-gradienm polymer network, resulting in broadband reflection for specific circularly polarized light. Additionally, its multi-domain planar texture eliminates the mirror-like reflection and produces diffusion reflection as well as a wide viewing angle. By optimizing the polymerization condition and cell thickness, we demonstrated that the proposed PSCLC diffuser exhibits a high reflectance of >35% in the reflective state and a low haze value of <20% in the transparent state. Both the reflective and transparent states of the PSCLC diffuser can be applied to the projection and transparent states of an active projection screen, respectively, wherein both states can be switched by driving the 90°-TNLC. Moreover, we built a projection-type transparent display system and demonstrated a pixelated image using the 90°-TNLC with a local pattern of ITO electrodes. The proposed active projection screen based on the highly polarization-selective reflective diffuser exhibits several unique optical characteristics. It can aid in advancing the existing projection-type transparent display technologies.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

Keywords

active smart screens, display quality, polarization modulator, polymer-stabilized cholesteric liquid crystal, ultra-broadband reflective diffuser

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