Technological Development of Liquid Crystal Smart Window

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ABSTRACT

We developed a versatile tristable smart glass based on cholesteric liquid crystal (CLC). It is voltage-switchable among three field-free stable states of different optical transmission properties. We also explore the applicability in full-color see-through displays. It is anticipated that the CLC smart glass can find widespread use.

1 INTRODUCTION

Smart glass emerges as a revolutionary technology that allows windows to dynamically manipulate daylighting, privacy, or climate of a building or to superimpose texts and graphics on real objects sitting behind the glass. Most of the existing smart glasses perform single functions, and single stable state in the absence of an applied field, requiring continuous power for operation.[1] For true energy conservation and versatility, a single device that can operate in different field-free stable modes to meet different haze and tinting needs is highly desirable but challenging.

CLCs are liquid crystals (LC) in which the molecules self-assemble into one-dimensional helices and are usually prepared by mixing a nematic LC with a chiral agent, which typically do not absorb visible light.[2] Different helix arrangements result in different optical textures; in a sandwich cell [Figure 1a], focal-conic (FC), lying-helix (LH), and planar (P) states are the dominant ones [Figure 1b]. For applications in which switchable tinting is desirable, one can dope the CLC with a dichroic dye and, through host–guest coupling, vary the alignment of dye molecules to control the tint level of the CLC cell[7].

We have developed a 'six-terminal' CLC smart glass, which comprises two embedded sets of common and interdigitated electrodes [Figure 1a] to access various field geometries[32,33] and is readily available at several LC-display manufacturers. In particular, such a CLC cell enables pure dielectric induction of uniform LH (besides the P and FC states) without the need for surface alignment, and all three states exhibit high field-off stability (over 3 years) independent of d/p. It is also noteworthy that, although CLCs have been extensively studied, most research focuses on the design and optimization of single targeted functions such as color tunability, switchable tinting, and dynamic haze control. Multi-functional and multi-stable CLCs and associated devices are not well explored. Our development of smart CLC glass focuses on the switching among the three field-free stable states to enable dynamic control of both tint and haze. In the following, we explore two potential applications of such a tristable optical switch: smart daylighting–privacy window and semi-static color-reflective window display.

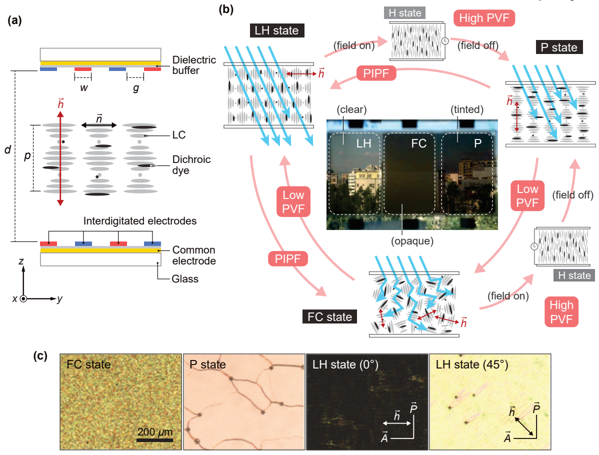

Fig. 1 (a) Schematic, (b) Photographs, drive scheme, and (c) Optical micrographs of dye-doped CLC.

2 RESULTS and DISCUSSION

2.1 Smart daylighting–privacy window and tristable switching

Figure 1b shows the city view seen through the smart glass (window) operating in three stable states: clear (LH), opaque (FC, for privacy protection), and tinted (P, for glare reduction). The six-terminal electrode configuration allows various field distributions, gradients, and drive schemes to be synthesized. Here, two switching modes—pulsed vertical field (PVF) and pulsed in-plane field (PIPF)—are utilized to enable the transitions among the cholesteric textures.

The two dark states, FC and P, are generated by PVF at different voltages, 80 and 120 V in the case of *Cell-NIR*. The low PVF (80 V) is used to randomize the original alignment of helices and form μm-sized FC domains which scatter light [Figure 1c]. Due to host–guest orientational coupling, any field-induced texture transition in the CLC is accompanied by a rearrangement of the dye molecules. The strong light scattering and absorption together make the smart window opaque as displayed in Figure 1b. Applying the high PVF (120 V) drives the CLC toward the P state. The window is, therefore, dark but still allows users to identify the objects behind the window [Figure 1b].

The clear state is generated by applying a PIPF (at 40 V for *Cell*-NIR) to induce a uniform LH alignment without involving EHD instabilities and surface alignment. In these regions, the applied field is highly tilted and more uniform than in the inter-electrode regions. The uniformity of the LH alignment can be greatly improved by spatially shifting the two interdigitated-electrode sets by half an electrode spacing to eliminate the “dead zones”, and a much lower haze is anticipated.

2.2 Optical characterization of tristable CLC with dichroic dye

The specular transmittance $T^{(s)}$ and haze H of the tristable CLC samples vary considerably among states (P: optical power, $T^{(s)} = P_{out,<2.5°}/P_{in}$, $H = P_{out,>2.5°}/P_{out}$). As shown in figure 2, the specular transmittances and haze values obtained for *Cell*-NIR are: $T_{LH}^{(s)} \approx 37$ %, $T_P^{(s)} \approx 12$ %, $T_{FC}^{(s)} \approx 11$ %, $H_{LH} \approx 11.9$ %, $H_P \approx 13.7$ %, and $H_{FC} \approx 78.7$ %. The reversible switching between the non-scattering LH (high $T^{(s)}$) and P (low $T^{(s)}$) states offers an effective way to control daylighting [Figure 1a]. To protect privacy, one can switch the smart window to the FC state; compared to the P state, the FC state exhibits similarly low $T^{(s)}$ of ~10 % but a very high haze of ~80 %. Such a tristable CLC window can allow full daylighting (in the LH state), reduce glare (in the P state), or create privacy (in the FC state) depending on one’s needs and can also be augmented to perform other functions such as projection- or waveguide-based window display.

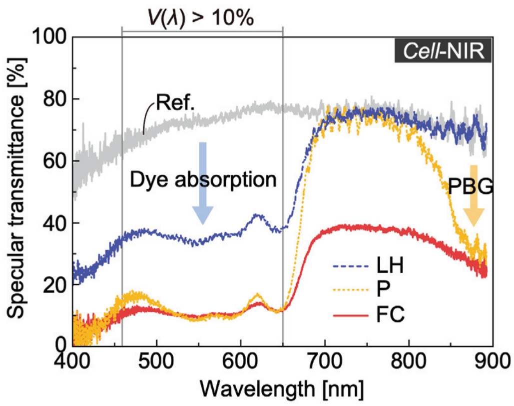

Fig. 2 Specular transmission spectra of Cell-NIR

2.3 Semi-static color-reflective window display

In the proof-of-concept demonstration, we employ three single-pixel dye-free CLC samples, *Cell*-B, *Cell*-G, and *Cell*-R [Figure 3]. These CLCs exhibit blue, green, and red color reflections in their P states, as shown in the top row of Figure 3a (the photographs are captured with bright and dark backgrounds). In the LH and FC states, all three cells are colorless and share similar transmission characteristics [Figure 3c]. The LH state is highly transparent with $T_{LH}^{(s)} \approx 73$ %, whereas the FC state shows low transparency with high haze, $T_{FC}^{(s)} \approx 23$ % and $H_{FC} \approx 74$ %. With pixelation, the CLC glass will be able to display bright color images with (colored) P and (white) FC pixels on a highly transparent LH background. These suggest that tristable CLC smart glass is promising for use as a semi-static see-through display on storefront window or vending machine.

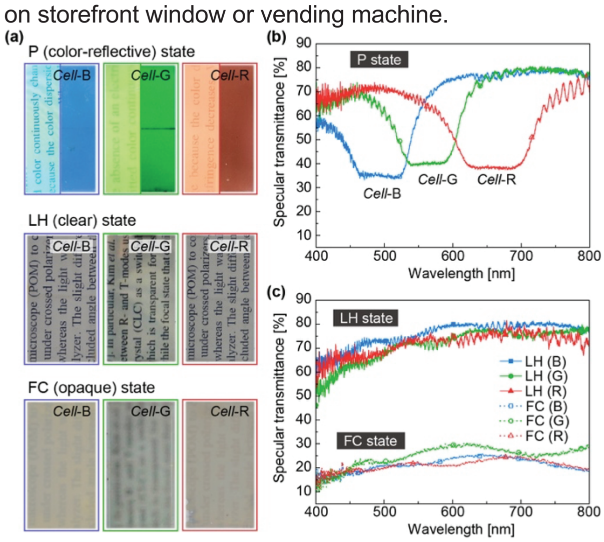

Fig. 3 Photographs and spectra of Cell-B, Cell-G, and Cell-R.

3 CONCLUSIONS

We have developed a CLC-based tristable smart glass that allows dynamic control of the optical transmission across the entire visible spectrum. The six-terminal electrode configuration enables tristable switching in CLCs of arbitrary helical pitches (and Bragg reflection colors), offering great versatility for practical applications. The smart glass can function as a window that is switchable among clear (LH), tinted (P), and opaque (FC) states for dynamic daylighting and privacy protection. It can also be adapted to construct full-color see-through displays, allowing one to create patterns and shading with color-reflective (P) pixels and white/black (FC) pixels on a highly transparent (LH) background. With the demonstrated versatility in design, we envision many more possibilities enabled by multistable CLC smart glass, such as solar-powered daylighting–privacy window and reflective–emissive window display.

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