

A Large-Size Flexible DDLC Dimming Automobile Sunroof based on PS Matrix Design[†]

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Abstract

Flexible dye-doped liquid crystal (DDLC) devices based on PS dot-matrix design have been realized by combining Roll-to-Roll (R2R) processing with ODF (One-Drop-Filling) vacuum alignment. Utilizing HTN normally-black dye liquid crystals, large-sized flexible dimming films with transmittance range from 1.1% to 24% were successfully produced. By optimizing the PS dot-matrix density to control the LC margin range and determining the appropriate amount of liquid crystal and lamination pressure, a large-sized double-curved automotive sunroof sample was fabricated by using conventional PVB lamination technology.

Author Keywords

Flexible DDLC; HTN Mode; Large-size; PS matrix design; Automobile sunroof.

1. Introduction

The application of smart dimming glass is becoming increasingly prevalent in the automotive industry, primarily in two scenarios: side windows and sunroofs. For side windows, due to their low curvature and predominantly single-curved design, glass-based dimming devices are compatible. However, automotive sunroofs, which typically feature double-curved shapes with larger curvatures to meet aerodynamic design requirements, face significant limitations when using glass-based dimming devices. This has driven the demand for the development of flexible dimming devices.

Among the existing flexible dimming technologies, four mainstream approaches are available: organic EC, SPD, PDLC, and DDLC. The first three technologies utilize gel-like or semi-solid material forms, which are compatible with Roll-to-Roll production processes for large-area manufacturing. In contrast, the DDLC technology retains its advantages of neutral black coloration, high transparency, and fast response by using liquid crystal material. Designing and manufacturing flexible liquid dimming devices has been a longstanding challenge in the industry. Between 2022 and 2023, BOE attempted to use Ball Spacer (BS) as spacers and successfully produced flexible DDLC dimming cells by laminating flexible sheets onto glass substrates^[1]. However, as shown in Fig.1, the significant challenges remain:

1. After film laminated to glass, the glass substrate undergoes multiple high-temperature baking processes, leading to severe warping. This can only be mitigated by reducing the lamination size, which greatly limits the size options for flexible devices.

2. When combining flexible dimming cells with automotive sunroof tempered glass using conventional PVB lamination processes, the spherical shape of BS

spacers and their weak adhesion to the film surface often result in sliding or aggregation during high-pressure lamination. This leads to non-uniform cell gaps of the flexible device.

Considering the demand for large-size applications and the stability of spacers during lamination, a new flexible device design and process method using Photo spacers as the primary solution has been developed.



Figure 1. (a) Flexible Cell with BS (b) BS sliding or aggregation during high-pressure PVB lamination

2. Device design & Material

The flexible device is manufactured using PET substrates with ITO coating, distinguishing between the upper and lower substrates. The upper substrate's ITO layer is patterned with a dot matrix of PS, made from specially developed high-modulus transparent dry film material.

The upper substrate may optionally have a PI alignment layer applied. On the lower substrate, a TN-type PI liquid layer must be uniformly coated across the entire surface of the ITO layer, followed by a rubbing process to create the alignment layer. The dye-doped liquid crystal is introduced, and the edge sealing adhesive is formed using ODF process and vacuum cell assembly method. As shown in Fig.2, the device uses a normally black mode dye-doped liquid crystal. Specifically, an HTN-type dye-doped liquid crystal with a d/p ratio of 6 is selected, and the cell gap is designed to be 15 μm . In the absence of voltage, the dye-doped liquid crystal molecules form a helical twist with the helix axis parallel to the cell thickness direction, maximizing multi-angle light absorption and achieving the dark state. When a driving voltage is applied, the helical twist unwinds, and the liquid crystal molecules align perpendicular to the substrate surface, achieving the bright state^[2].

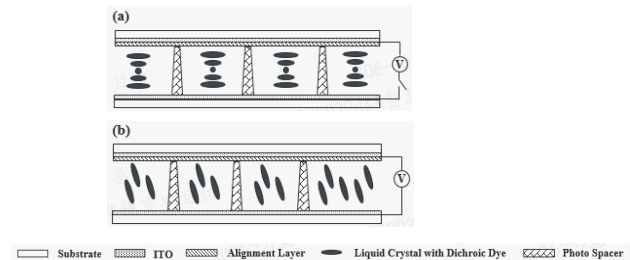


Figure 2. (a) HTN mode cell when voltage off (b) HTN mode cell when voltage on

Based on the structural modulus parameters of various materials, Comsol was used to conduct a deformation

simulation on the device structure that includes a PET film and a dry film PS lattice. It is estimated that the overall deformation under one atmospheric pressure is 0.27 μm , corresponding to an LC Margin range of approximately 2%.

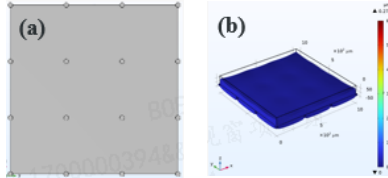


Figure 3. (a) PS Matrix design in 1mm² (b) Deformation Simulation by Comsol

3. Process Route Description

As Shown in Fig.4, the newly developed process integrates R2R production with sheet-based ODF vacuum cell assembly.

For the upper substrate, the dry film PS dot matrix is fabricated using an R2R process. A roll of transparent dry film is thermally laminated onto the surface of ITO-coated PET. This is followed by exposure, development, and baking to form a specific dot matrix pattern.

For the lower substrate, a layer of PI liquid is coated onto the surface of the ITO-coated PET and thermally cured.

Both the upper and lower PET substrates are then cut into sheets of specific dimensions. The sheets are laminated onto glass substrates using adhesive film. The lower glass substrate with the PET sheet undergoes a PI rubbing alignment process, after which dye-doped liquid crystal is dispensed. Simultaneously, the upper substrate undergoes the process of sealant dispense. The upper and lower substrates are aligned and assembled in a vacuum environment, and the sealant adhesive is cured to complete the cell assembly process. The laminated glass substrate is then heated to release the adhesive film, allowing the assembled flexible cell to be separated from the glass substrate. Finally, the flexible cell is mechanically cut to shape, and bonding pads are formed. The process concludes with the FPC bonding step.

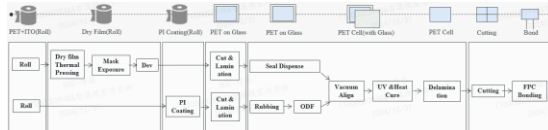


Figure 4. Schematic diagram of Process Route

4. Sample Property and Lamination Test (a) Dimming Property of Flexible DDLC Cell

A flexible cell with dimensions of 240×240mm was fabricated, and the voltage was gradually increased from 0V to 30V in 1V increments. The transmittance and haze values under different voltages were measured, as shown in the Fig.5.

From the VT and V-Haze curves, it can be observed that the HTN liquid crystal used in this test, due to the relatively high amount of chiral dopant, exhibits the following behavior: Between 7V and 24V, as the

transmittance gradually increases, the haze remains at approximately 20%. In this voltage range, the dye-doped liquid crystal molecules are in a Focal Conic texture state, while the disordered arrangement of liquid crystal molecules leads to a high haze effect. When the voltage exceeds 24V, the haze value rapidly drops to below 3%, and the transmittance value approaches its maximum. At this stage, the dye-doped liquid crystal molecules transition to a homeotropic texture state under high voltage.

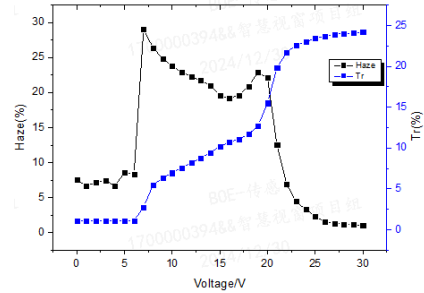


Figure 5. VT and V-Haze curves of Flexible DDLC Cell

The actual dimming images of the flexible cell at 0V and 27V are shown in Fig.6 below. At 0V, the transmittance of the flexible film is 1.1%, and the haze is 7%. At 27V, the transmittance reaches 24%, and the haze is reduced to 1.3%.

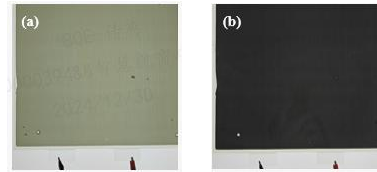


Figure 6. (a) Bright State at 27V (b) Dark State at 0V

(b) LC Margin range Test

Table 1 shows sample images of the flexible DDLC cells with different LC amounts. When the LC amount is at 0%, a noticeable "Not Fill Bubble" phenomenon is observed. As the LC amount increases, a slight "Overfill Mura" begins to appear at 2%, and this effect becomes more pronounced at 4%.

Based on the measured results, the LC Margin range is determined to be approximately 1% ± 1%. This aligns closely with the LC margin range of 2% predicted by the Comsol deformation model.

Table 1. Sample images of flexible DDLC Cells with different LC amounts

LC Amount	0%	2%	4%
Sample Image			
Judge	Not Fill Bubble	Overfill Mura (Light)	Overfill Mura (Heavy)

(c) Lamination results of different LC Margin

Flexible films with liquid crystal amount of 0%, -2%, -4%, -8%, and -10% were selected for lamination process trials. The lamination structure follows a sandwich interlayer design, as shown in the Fig.7 below. The lamination was performed using 300×300 mm tempered glass and two PVB interlayers commonly used in automotive safety glass, with a thickness of 0.76 mm. The laminating process conditions are the same as the PVB laminating process adopted for conventional automobile safety glass. The laminating temperature is 145 °C, the pressure is 12 bar, and the holding time is 45 minutes.

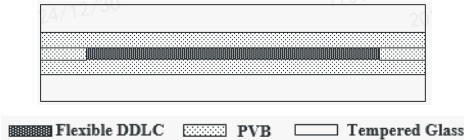


Figure 7. Lamination structure of Flexible DDLC cell with PVB and Tempered

Table 2. Mura Results of different LC Amount Cells before & after Lamination with PVB

LC Amount	Before Lamination	After Lamination	Judge
0%			Overfill Mura
-2%			Overfill Mura
-4%			OK
-8%			OK
-10%			OK

As shown in the Table 2:

- Before lamination, samples with lower liquid crystal amount exhibited a high incidence of "Not Fill Bubble" defects, which became more severe as the liquid crystal amount decreased.
- After lamination, samples with 0% and -2% liquid crystal amount exhibited black spots, resembling the "Overfill Mura" defects typically seen with excessive liquid crystal amount.
- In contrast, samples with -4%, -8%, and -10% liquid crystal amount showed no "Not Fill Bubble" after lamination, and no "Overfill Mura" defects were observed.

These results indicate that the lamination process applies external pressure exceeding 1bar to the flexible cell, causing the cell gap of the cell to decrease. For cells with initially low liquid crystal amount and "Not Fill Bubble"

defects, the pressure during lamination forces liquid crystal to passively diffuse further. When the liquid crystal amount matches the reduced cell gap, the laminated sample achieves a mura-free state. This demonstrates that achieving a mura-free flexible DDLC cell lamination requires proper optimization of both liquid crystal amount and lamination pressure.

(d) Lamination results of large-sized sample

Based on the above lamination test results, the flexible dye liquid crystal cells with a large size of 1100 * 1000 mm were used for lamination. The tempered glass used for lamination was double-curved white glass, and the camber heights in both the X and Y directions were above 19 mm/m. The dimming states of the laminated samples under the voltage of 0V and 27V are shown in the following Fig.8.



Figure 8. (a) Bright State at 27V (b) Dark State at 0V

5. Conclusion

The flexible dye liquid crystal devices based on the PS design have better compatibility with the lamination process of PVB than BS design, and are easier to achieve the manufacturing process of large-sized products. Based on Comsol modeling and reasonable control of the PS lattice design, it can not only improve the support strength of the film under normal pressure and high lamination pressure, but also realize the control of the LC margin range of the flexible film. Appropriate LC amount and the matching lamination pressure are important factors for achieving lamination of flexible liquid DDLC without mura.

6. References

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