Functionality Enhancement for e-Privacy Display

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Abstract *Electrically switchable privacy laptop displays have been commercialised by multiple manufacturers, creating demands for extended functionality and other applications. Enhanced privacy display optical component stacks are presented including (i) a diffractive liquid crystal directional control retarder with share mode luminance >10% and privacy mode security factor >1; (ii) cost reduced retarder stack architectures for automotive cabin displays and point-of-sale terminals; and (iii) a patterned switchable retarder for off-axis display branding.*

Keywords *Privacy, switchable, display, security, directional, liquid crystal, retarder, diffractive, guest-host, LCD, laptop, backlight, PID, automotive, vehicle, driver, passenger, co-driver, infotainment, logo, branding, point-of-sales, POS.*

1. Introduction

Optical stacks for electrically switchable privacy (e-Privacy) displays offer (a) a narrow-angle single user privacy mode for example for laptops, or a No Driver Distraction (NDD) mode for automotive passenger infotainment displays (PID); and (b) a wide-angle share mode, for multiple viewers.

Recently reported e-Privacy optical stacks include:

- *Louvre & Scatter.* A backlight output is angularly restricted by a micro-louvre film. Scattering optics are then added such as a wide angle lightguide[1], a switchable PDLC diffuser[2,3], or a switchable LC grating[4]. In privacy mode the scattering optics are intended to be clear; while in share mode they scatter light.
- *Out-of-plane polariser film* and a liquid crystal polarisation rotator[5] to provide a rotatable off-axis absorption profile.
- *Switchable Liquid Crystal Retarder* (SLCR)[6,7] arranged between a pair of polarisers, uses phase modification to switch between off-axis absorption and transmission while not modifying on-axis performance. An optional reflective polariser adds switchable off-axis reflectivity, significantly suppressing image visibility to snoopers in the narrow-angle mode with minimal impact in wide-angle mode. With higher transmission and lower thickness than the above approaches, SLCRs are well proven in manufacture for laptop displays, having shipped many millions of units.

PIDs have some key differences to laptop displays. In NDD mode, stringent demands are placed on image invisibility as the driver leans towards the passenger; however when the driver requires to see the display, high luminance and colour uniformity is essential. These competing demands have led to various approaches for asymmetric light control [7,8,9] with SLCRs.

The quantification of image visibility suppression for the human visual system (HVS) have been described previously [6,7]. The *security factor*, S at a given polar viewing angle (θ, ϕ), is given by:

$$S(\theta,\phi) = log_{10}\left(1 + \frac{\alpha.\rho(\theta,\phi)}{\pi.P(\theta,\phi)}\right) \qquad \text{eqn. (1)}$$

where $\rho(\theta,\phi)$ is the display reflectivity, $P(\theta,\phi)$ is the ratio of the display luminance $Y(\theta,\phi)$ to the peak luminance, Y_0 and α is the ratio I/Y_0 where $I(\theta,\phi)$ is the ambient light source illuminance at the display front surface that is reflected towards the snooper and is independent of viewing angle for Lambertian illumination.

HVS investigations indicated privacy mode security factor S_P>1 provides a reliably secure image to an off-axis snooper and share mode security factor S_S<0.2 provides satisfactory image contrast to an off-axis user.

With the underlying technologies and performance metrics now maturing, the authors have sought to enhance the user experience, and to expand the application space to include, PID and point-of-sale (POS) displays. Refined optical stack designs are considered here, and results of demonstrations or pre-production units are presented.

2. Share mode enhancement

2.1 Wide-angle visibility trade-offs

In commercial privacy displays using LCD, SLCRs are combined with controlled collimation backlights that use grazing angle extraction from waveguides and light turning films[10].

In share mode, typical off-axis luminance (P_S~3%, ρ_S~5%, α~1 lux/nit at θ=45º) gives S_S~0.2 – i.e. a clearly visible, if slightly dim, image. Share mode visibility can be improved by increasing display luminance Y_0 (i.e. reducing α and therefore S_S), however this can give an overly bright image to the head-on-user and increases power consumption.

Widening the backlight luminance profile so that $P(\theta$=45º)>10% to give S_S<0.1 could be considered, however single SLCRs have a minimum transmission (and maximum reflectivity) such that S_P falls below the 1.0 threshold and the display is no longer private.

Optical stacks with multiple SLCRs in series can readily deliver S_P>1 when combined with wider backlights but add cost – therefore the challenge has becomes how to deliver improved share mode with a single SLCR.

2.2 Diffractive SLCR (D-SLCR)

Figure 1 shows a new Diffractive SLCR (D-SLCR) which adds a dielectric and high-resolution patterned electrode to the dual layer uniform electrodes of a conventional SLCR, however with similar LC and passive retarder specifications.

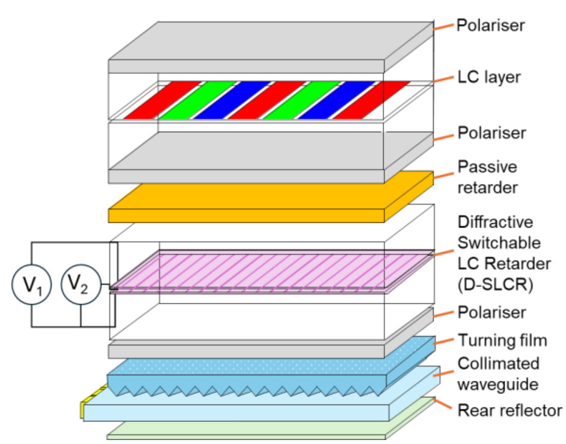

Figure 1. D-SLCR switchable privacy display

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In the privacy mode of Figure 2, the electrodes are driven so that the LC retarder director profiles are uniform across the LC layer but have controlled splay through the layer. Between parallel polarisers, on-axis light is transmitted and off-axis light absorbed, as for a conventional SLCR[6].

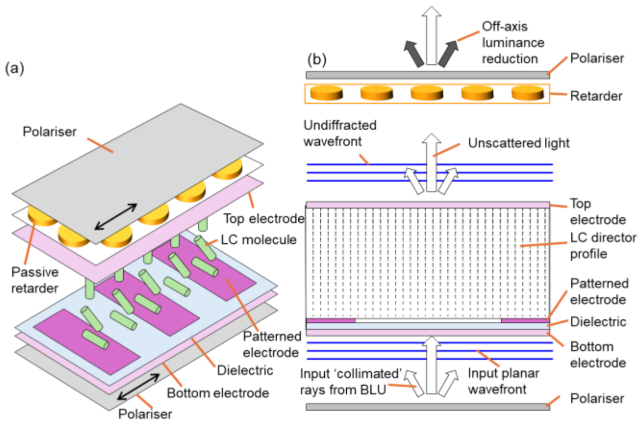

Figure 2. Operation in privacy mode (a) LC alignment in D-SLCR (b) wavefront & luminance control

Figure 3 shows the share mode with D-SLCR driven with a structured phase profile that diffracts input wavefronts. The out-of-plane alignment structure is arranged to minimise off-axis phase changes that, if present, would cause off-axis absorption between the parallel polarisers – light from the backlight is scattered to wide-angles but not absorbed.

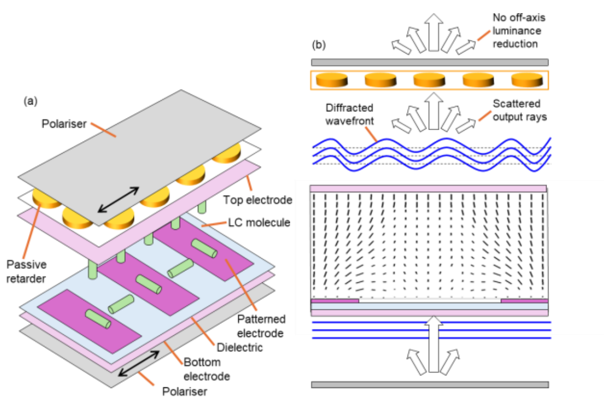

Figure 3. Operation in share mode (a) LC alignment in D-SLCR (b) wavefront & luminance control

Figure 4 illustrates the simulated diffraction profiles at different control voltages.

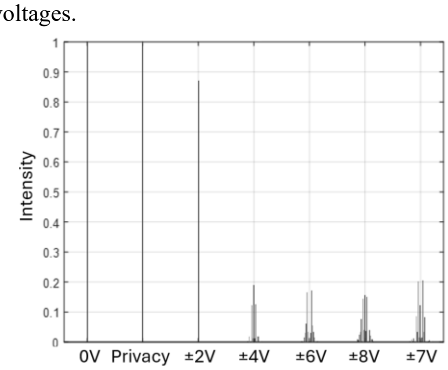

Figure 4. Simulated diffraction power spectra for various drive voltages, 3.2° order separation

The cluster of discrete bars in this figure represent the diffraction orders spaced by $\approx \lambda/p$ radians (p being the electrode pitch of 10μm in this example and λ the wavelength of visible light). In privacy mode setting, only the zero order component is transmitted with no unwanted scatter. In the high voltage drive states, the phase profile across the LC layer is established and light is diffracted, with some control of the degree of scatter achieved.

Measurements from a display build are shown in Figure 5, showing the 10% at 45° luminance share mode target is achieved, and in privacy mode a privacy level P of 0.27% gives a security factor S_P=1.1 at α=2 lux/nit.

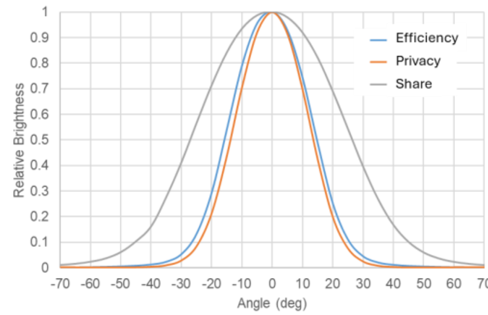

Figure 5. Measured luminance profiles

The D-SLCR can also be used for a 'high efficiency' mode as shown in Figure 6. This operates in the same way as the share mode of a non-diffractive SLCR and is useful in environments where the widest share mode performance is not critical so that the head-on display luminance and power efficiency are optimised.

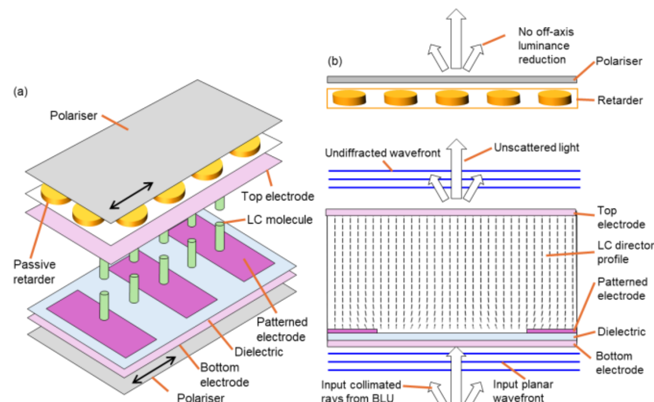

Figure 6. Operation in efficiency mode (a) LC alignment in D-SLCR (b) wavefront & luminance control

2.3. Guest-Host SLCR (GH-SLCR)

The SLCRs described above rely on off-axis absorption in the output polariser arising from phase shifts through the LC layer that depend on the viewing angle.

Figure 7 illustrates the introduction of an absorptive dichroic dye guest material into the LC layer host material[11]. The dye is aligned by the LC molecules such that as well as angular phase modification, off-axis light is partially absorbed within the LC layer itself, increasing the off-axis contrast in the GH-SLCR.

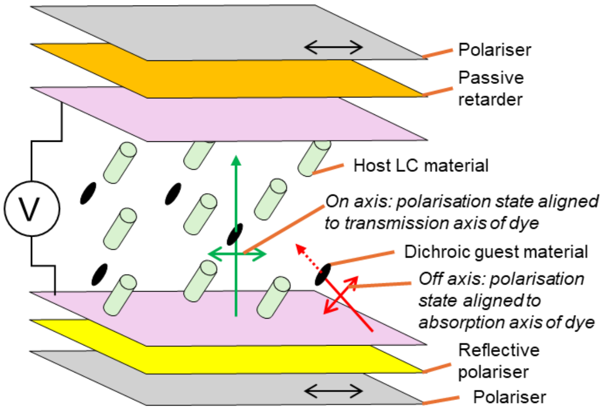

Figure 7. GH-SLCR increases off-axis light absorption within the LC layer

Figure 8 illustrates the modified transmission profile of the GH-SLCR in privacy mode. In optical stack design, this can be used to modify the backlight luminance profile, increasing its off-axis luminance, e.g. using BEF backlight stacks rather than light turning film stacks reducing cost.

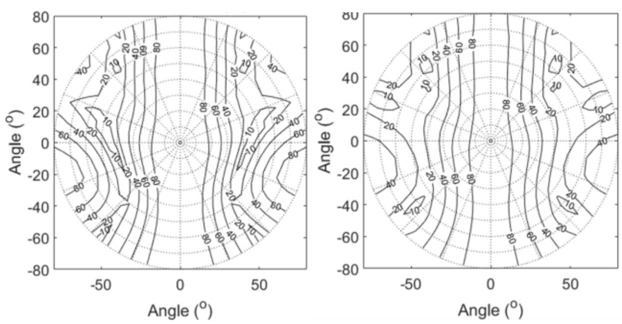

Figure 8. GH-SLCR provides improved luminance reduction, particularly at higher angles

A shipping display using a GH-SLCR is shown in Figure 9.

Figure 9. Shipping 5.8" POS privacy display incorporating BEF backlight stack and GH-SLCR

3. Aesthetic enhancement

3.1 Display Screen Branding optical stack

In applications such as on the dashboard of a vehicle, in a point-of-sales environment, or in a sales showroom, the 'empty black rectangle' of switched-off displays can present an undesirable aesthetic and/or potentially unused real estate for display branding.

Similarly, it is not always visually clear to users (or snoopers) that the display is operating in privacy mode, some reassurance of that fact has been found to be helpful.

Figure 10 shows an alternative privacy display structure, termed *Display Screen Branding*^{TM} [12] with an SLCR comprising a switchable pattern in the drive electrodes. The SLCR can alternatively be the D-SLCR or the GH-SLCR described above.

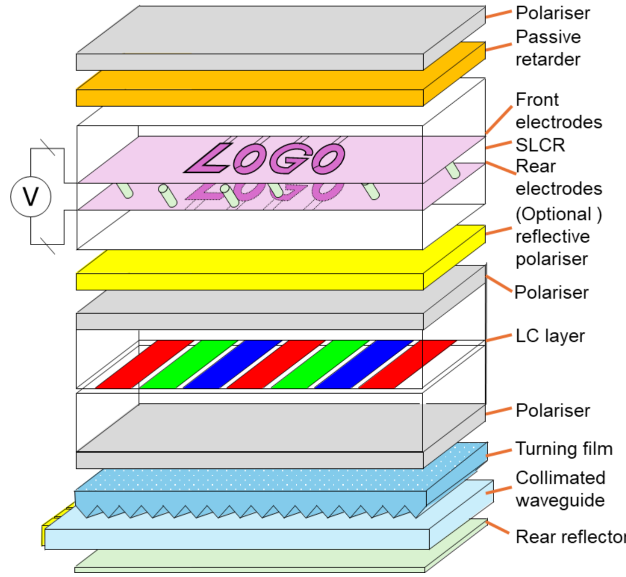

Figure 10. *Display Screen Branding* optical stack

3.2 Electrode layout

Figure 11 shows electrode patterns for each side of the SLCR.

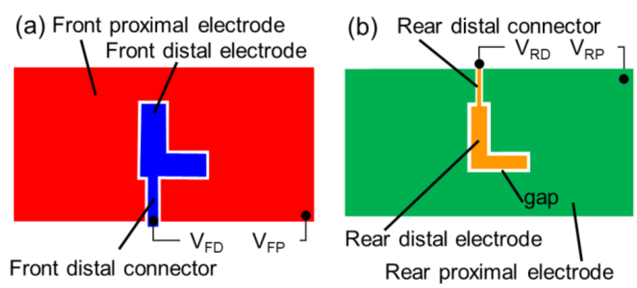

Figure 11. (a) Front (b) Rear electrode layouts

A *distal pattern* electrode (the '**L**'), separated from the display edge and a *distal connector* electrode; is surrounded by a *proximal* electrode. The distal pattern and connector electrodes are separated from the proximal electrode by gaps of width similar to the cell thickness for 'gap switching' so the LC layer is uniformly driven when both proximal and distal electrodes are driven with the same signal. Note that the distal connector electrodes do not overlap, but the distal pattern electrodes are aligned.

The SLCR drive voltages V_{FD}, V_{RD}, V_{FP}, V_{RP} are set with amplitude and phase so that the LC layer between *overlapping* distal pattern electrodes is driven in a first state whereas the LC layer between the remaining overlapping electrode regions (distal connector/proximal or proximal/proximal) is driven in a second state.

Some of the different modes of operation of the SLCR are illustrated in Figure 12 which shows the transmissive or absorbing/reflective regions, illustrating that the connection electrodes become hidden by the drive scheme, giving wide scope for pattern design.

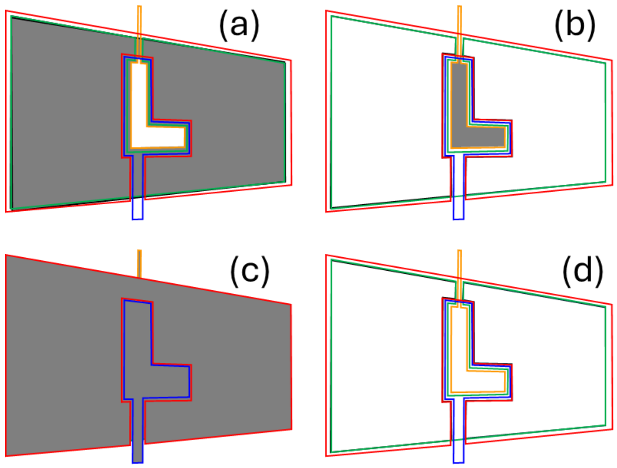

Figure 12. SLCR modes of operation: (a) Pattern (b) Inverted Pattern (c) Uniform Privacy (d) Uniform Share

3.3 Operation modes

Some of the potential operating modes are shown in Figure 13. In each mode, the head-on viewer sees no visibility of the electrode pattern, the patterns are only visible for off-axis locations.

In Privacy and Share mode operation, the pattern may be completely hidden. Alternatively, a low contrast pattern (for example $\Delta S_P<0.05$ between distal and proximal regions) may be displayed to confirm that the privacy mode display is functioning.

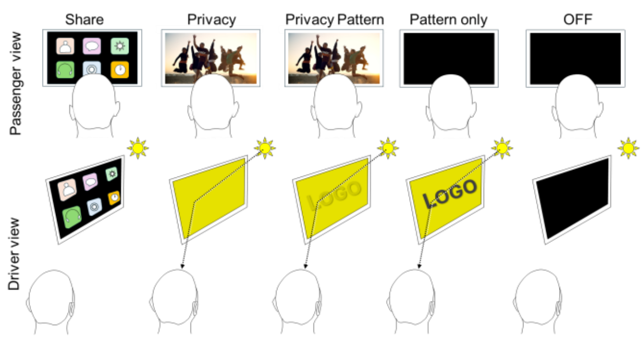

Figure 13. Operating modes

Figure 14 shows a POS display operating in Pattern mode when the backlight/panel is switched off, giving an extremely low power mode using only reflected ambient light. In other examples: a vehicle PID may show the driver artwork or branding; a mobile device may show a low power 'device on' indication; and in a retail environment, displays may operate for extended periods without being plugged into a mains supply while delivering branding.

Figure 14. Photo of *Display Screen Branding*™ technology in a point of sale (POS) application.

4. Conclusion

With e-Privacy displays firmly established in LCD laptops and now pushing into new applications, valuable new functionalities can be realised.

For backlit LCD a new diffractive switchable LC retarder is shown to increase share mode luminance from <3% to >10% at typical off-axis user viewing angles.

A guest-host switchable liquid crystal retarder enables switchable privacy modes using commodity backlights, enabling lower display system cost.

To mitigate the 'empty black rectangle' of conventional displays when switched off, a unique Display Screen Branding architecture has been developed, enabling off-axis viewing of brand artwork, messages or logos e.g. for automotive cabins and retail environments at minimal power consumption without driving the underlying display panel. Electrode configurations and drive schemes conceal the presence of connections to the patterns, achieving unique design freedom for display branding.

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