

Switchable Privacy Display Design and Optimisation

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Abstract

The visibility of electronically controlled switchable privacy display to both primary viewers and unwanted observers (snoopers) is reviewed and a method for comparison of privacy display performance is proposed. We report results from privacy display optical stacks that employ luminance and contrast control using directional backlights, switchable retardance stacks and liquid crystal pixel bias voltage control.

Keywords

Privacy; display; contrast sensitivity; LCD; Intelligent Backlight Technology; perceived dynamic range; liquid crystal; retarder.

1. Introduction

The need to work with private and sensitive information in public environments continues to expand as users become ever more reliant on mobile working and personal display devices. New optical privacy display technologies to limit “visual hacking” have therefore increased in importance for the displays industry.

Recent work towards electronically switchable privacy displays can be categorized as providing either luminance or contrast control of the image seen by the snooper.

(i) *Luminance control* including directional LCD backlight technologies^[1,2], that switch between narrow and wide angle luminance profiles in a lateral direction; and field-of-view (FOV) technologies using electronically controllable birefringence layers^[3] that modify display polar luminance profiles.

(ii) *Contrast control* including a time multiplexed directional backlight and fast LCD^[4], that delivers contrast reduction by sequential display of positive and negative images to snooper; and bias controlled LCD^[5] that switches from in-plane to out-of-plane LC director orientations, reducing the intrinsic wide viewing of liquid crystal display modes such as FFS and IPS.

While the concept of a privacy display is well understood, to the knowledge of the authors, desirable performance levels and appropriate characterisation and quantification methods are not well reported or accepted.

2. Image visibility for snoopers

2.1 Contrast sensitivity

The modulation transfer function is established as a method of characterising the resolution capability of optical systems. In privacy display, we adapt similar concepts to evaluate the limits of image readability for an unwanted observer (a snooper).

The human visual system can adapt to more than seven orders of magnitude dynamic range so is highly adept at dealing with luminance changes in the environment. From the contrast sensitivity curves illustrated in Figure 1, benchmarks can be established for the visibility of a privacy display to a snooper.

A worst-case but common usage for privacy display is viewing spreadsheets and presentations on a laptop in a dimmed aircraft cabin, with an off-axis snooper at about 1m from a display. The peak contrast sensitivity occurs for spatial frequencies that are typically used for title font sizes, business logos and faces. For privacy displays that use luminance control as discussed below, the

contrast sensitivity does indeed reduce with reducing snooper image luminance, but such images remain legible at snooper image luminance well below 1nit, both for human observers, and for photographic snooping.

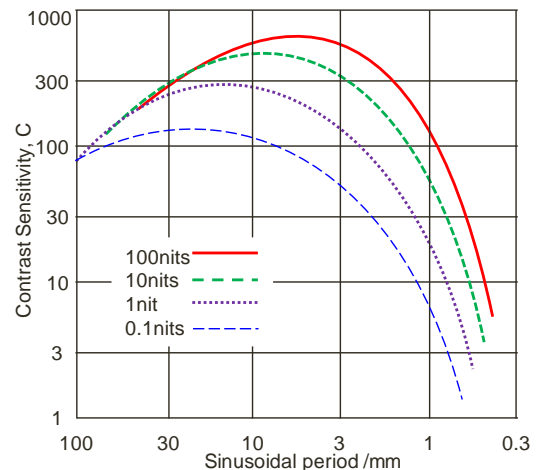


Figure 1. Fitted profiles for Contrast Sensitivity^[6] (reciprocal threshold contrast) for varying display luminance as seen by an off-axis snooper 1m from a display in a dark room.

For privacy displays showing static images, the peak contrast sensitivity ratio may approach 500 implying a (worst case) grey level resolution of less than 0.2% of the total white state luminance would be needed to give full image obscuration to the snooper. For video content privacy protection, spatio-temporal effects are a subject for future analysis.

2.2 Characterisation of display privacy

Figure 1 suggests that comprehensive privacy protection by control of luminance or contrast alone is highly challenging for privacy display designers. The authors propose metrics below that can compare the performance of different privacy technologies.

In the present analysis for a lateral angle θ and elevation ϕ , *Privacy Level*, PL and *Privacy Contrast Ratio*, PCR are given by:

$$PL(\theta, \phi) = Y_D(\theta, \phi) / Y_D(0^\circ, 0^\circ) \quad (1)$$

$$PCR(\theta, \phi) = Y_D(\theta, \phi) / K_D(\theta, \phi) \quad (2)$$

where Y_D , K_D are the respective white and black state display luminance measured in a dark environment. Typical polar coordinates of interest for privacy display are zero elevation lateral viewing locations ($\theta = \pm 45^\circ$, $\phi = 0^\circ$) and downwards viewing quadrants ($\theta = \pm 45^\circ$, $\phi = +45^\circ$).

Figure 2 illustrates display operation for dark ambient with a luminance-controlled privacy display, head-on contrast ratio 1500:1, and head-on luminance of 150nits. Maximum white state luminance to a snooper is 0.75nits for a PL($45^\circ, 0^\circ$) of 0.5%. For a PCR($45^\circ, 0^\circ$) of 500 (representative of an IPS panel off-axis), the display content is clearly legible to the snooper.

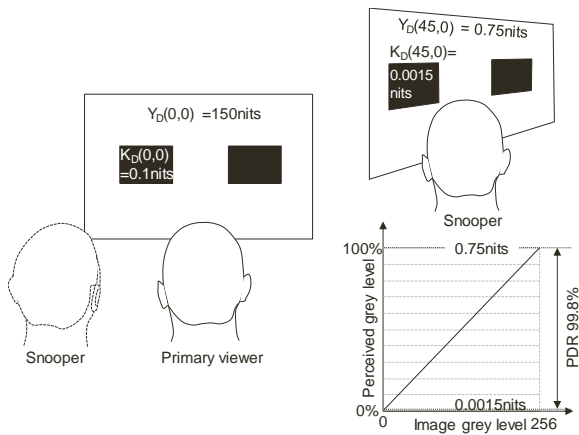


Figure 2. Image visibility for operation of a luminance controlled privacy display in a dark ambient environment for the primary viewer (left) snooper (upper right) and perceived grey scale response (lower right).

2.3 PDR & ambient illuminance

Here we introduce the term *Perceived Dynamic Range*, (*PDR*) for the visibility of the privacy image by evaluating the mapping of the image input grey level to a perceived grey level in the visual system of the snooper whether by human visual system or photographic snooping.

The PDR of a luminance and contrast controlled privacy display with ambient illumination is defined in Equation 3 for a given polar location (θ, ϕ);

$$PDR(\theta, \phi) = \zeta \cdot (Y_D(\theta, \phi) - K_D(\theta, \phi)) / R_A(\theta, \phi) \quad (3)$$

where for a Lambertian front diffuser with minimum reflectivity of 4% of ambient illuminance I_A , the minimum total ambient white state R_A including frontal reflections is given by Equation 4;

$$R_A(\theta, \phi) = Y_D(\theta, \phi) + 0.04 I_A / \pi \quad (4)$$

and ζ is a contrast visibility factor that is dependent on the perceived contrast of an image spatial frequency ν to the snooper.

In the limit of threshold image contrast, ζ can be determined by Equation 5 which gives the ratio of contrast sensitivity to a snooper for spatial frequency ν , to the peak contrast sensitivity at frequency ν_p seen by the primary viewer;

$$\zeta(\nu, \theta, \phi) = C(\nu, \theta, \phi) / C(\nu_p, Y_D(0, 0)) \quad (5)$$

For the purpose of the analysis presented here, typically the snooper observes images at contrast ratios that are significantly above threshold, and visibility of any image details are undesirable so the worst case of $\zeta=1$ is assumed.

Returning to Figure 2, for a snooper observing the display in a fully dark ambient environment ($R_A = Y_D$), the $PDR(45^\circ, 0^\circ)$ is 99.8% for the representative 500:1 display viewed off-axis. That is, the snooper perceives most of the displayed grey levels that are delivered to the primary viewer, accounting for its relatively high legibility.

In more frequent usage cases, such as office environments and other public spaces, ambient illuminance is reflected from the front of the display to the snooper. The ambient illuminance I_A contributes to a perceived white state luminance R_A that adds to the underlying white state Y_D and reduces the PDR. Figure 3 illustrates frontal ambient illumination of a typical contrast

controlled privacy display with a conventional backlight. In this example, the contrast is shown as inverting at the snooper location.

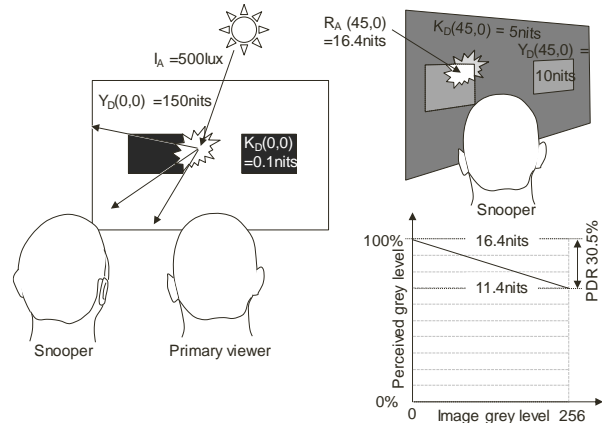


Figure 3. Privacy display performance assessment for a contrast controlled privacy display and ambient illuminance.

Here a linear PDR mapping has been illustrated; however, colour gamut reductions at the lower luminance levels, visual defects and non-linear grey scale gamma mapping can cause image degradations to the snooper. Further, non-Lambertian reflections such as from touch screens can increase reflectivity R_A over regions of the display and provide image camouflage.

A future analysis will incorporate a more sophisticated mapping function between displayed pixel values and perceived image to the snooper.

Figure 4 shows simulated performance of various privacy displays with a Lambertian front diffuser, or equivalently for a uniform large area illuminant. This graph can be used to compare the relative merits of different privacy displays, sensitivity to viewing angle changes, tuning of display usage cases, spatial frequency dependency, and dependency on ambient lighting conditions.

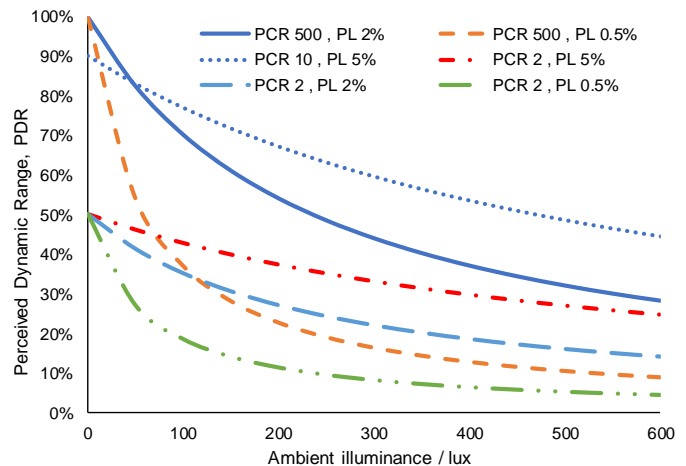


Figure 4. Simulated PDR against Lambertian ambient illuminance for a snooper viewing a 150nit privacy display for various privacy contrast ratios, PCR & privacy levels, PL.

3. Luminance controlled privacy displays

3.1 Intelligent Backlight Technology (IBT)

The authors previously reported the application of *Intelligent Backlight Technology*^[1] (IBT) to a switchable privacy display. IBT uses an addressable linear array of LEDs at the input of an imaging directional light guide plate (D-LGP), and a micro-

structured high brightness film (HBF) that together direct structured light fields through a liquid crystal display. By control of the illumination across the array of LEDs, off-axis luminance control can be provided, typically in the lateral (ϕ) direction.

3.2 IBT luminance controlled privacy display

A typical luminance controlled privacy profile for an IBT display is illustrated in Fig.5.

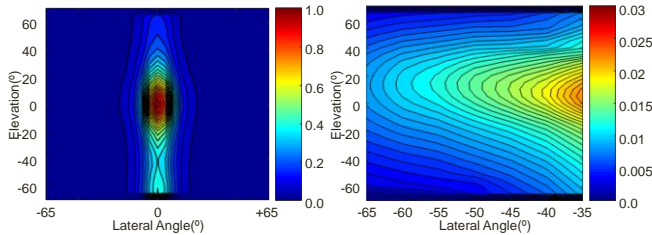


Figure 5. Measured luminance profile of IBT in Privacy mode normalised to head on central luminance $Y_D(0^\circ, 0^\circ)$.

From the above analysis of contrast sensitivity, customer feedback and the authors' own observations, such privacy levels work well in brightly lit environments but at viewing angles above 45° lateral viewing angle do not quite match PL and PDR that can be achieved with the leading passive micro-louvre film.

3.3 ECB luminance controlled privacy display

Polar luminance control has been reported previously for a cell phone application^[3] by addition of an electrically controllable birefringence (ECB) liquid crystal layer and an extra polariser to a conventional wide angle backlit LCD.

While the wide angle mode is minimally affected, only limited privacy mode capability was reported due to the "bull's eye" shaped low transmission regions of the polar luminance profiles with small field-of-view (FOV). This is confirmed by simulation as illustrated in Figure 6. High transmission is observed at lateral angles ($\theta > 50^\circ, \phi = 0^\circ$) and as such provides a rather weak privacy function, with typical PL of 5~10% observable by a snooper.

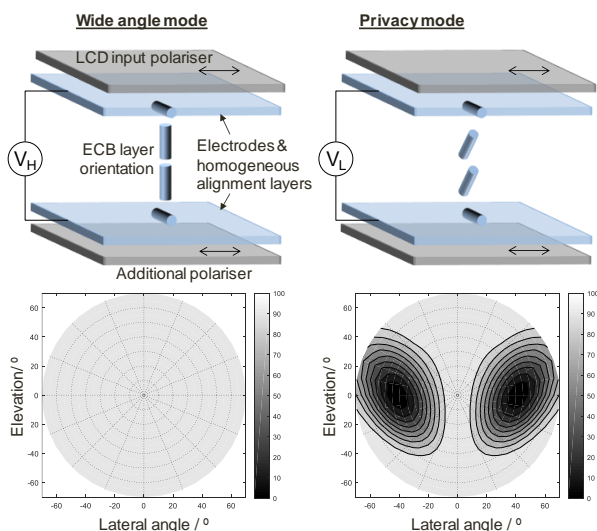


Figure 6. ECB mode LC cell optical stack design (above) and 10% step iso-transmission profiles (below).

3.4 IBT-eQ mode

Insertion of a controllable retarder into the optical stack of IBT as illustrated in Figure 7 provides a multiplicative improvement in

privacy performance, particularly in viewing quadrants where snoopers are often located. IBT-eQ compensated retardation stack technology can also be applied to other types of backlights with reduced off-axis luminance such as those using collimating light guide plates and turning films^[7].

IBT-eQ displays use proprietary retarder stack designs that include a combination of passive retarders and switchable liquid crystal structures to achieve superior FOV performance. An example that uses homeotropic LC cell alignment and discotic C plate retarders, is illustrated in Figure 8 and shows that substantial improvement in privacy performance can be achieved. Further, zero voltage operation is obtainable in the wide angle mode, reducing the maximum power consumption of the system.

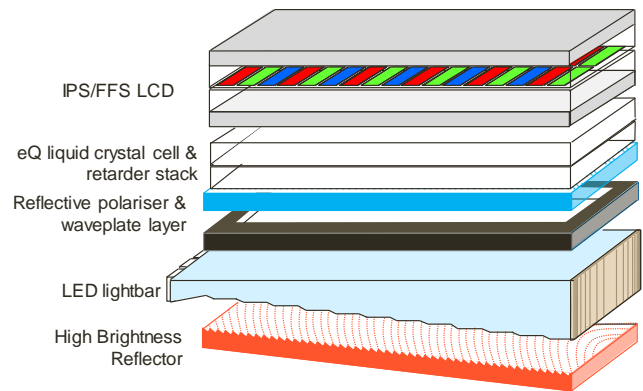


Figure 7. IBT-eQ privacy display structure incorporates a controllable retarder stack between the reflective polariser and LCD input polariser of IBT.

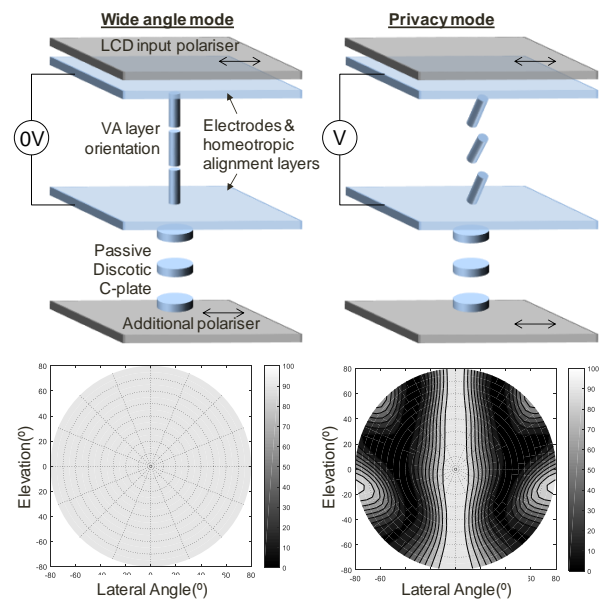


Figure 8. Homeotropic alignment and discotic compensation films reduces privacy levels with essentially full head on luminance.

The PDR of the IBT-eQ system using the stack-up of Figure 8 is shown by the curve PCR500, PL0.5% in Figure 4, illustrating class leading performance in office environments for displays with luminance control only. Total IBT stack optimisation has been shown to provide privacy levels over a wide field of view with $PL(45^\circ, 0^\circ) < 0.5\%$ and $PL(45^\circ, 45^\circ) < 0.5\%$, as shown in Figure 9.

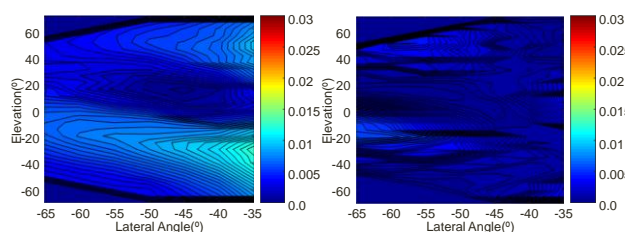


Figure 9. Privacy level, PL field of view plots for the simulated IBT-eQ stacks of Figure 6 (left) & Figure 8 (right), normalised to Y_D .

4. Contrast controlled privacy displays

As described in section 2.3 and illustrated in figure 4, for Lambertian illuminance levels below about 100lux, even high performance luminance controlled displays may not give sufficient privacy from a snooper.

4.1 IBT Privacy+ technology

IBT Privacy+ operation has been previously reported^[4] and provides both luminance and contrast controlled privacy by time multiplexed operation in which alternating positive and negative images are synchronised with LED illumination at image update rates of 100Hz or greater. A typical IBT performance level is illustrated by the curve PCR2, PL2% in Figure 4. In combination with IBT-eQ technology, yet further gains in performance can be achieved with PCR2, PL0.5% representing an optimum approach to privacy across a wide range of ambient lighting conditions.

4.2 LCD biased pixel technology

An alternative approach to off-axis contrast control uses director tilt modification of the liquid crystal layer in LCD panels^[5]. In-Plane-Switching (IPS) LCD panels that offer excellent angular contrast in wide angle operation can be operated with reduced contrast for off-axis viewing by applying a voltage across the LC cell and forcing some out-of-plane molecular reorientation.

A simulation of out-of-plane liquid crystal retardance was used to investigate variation of contrast with viewing angle, with a constraint of $PCR(45^\circ, 0^\circ) = 1.0$.

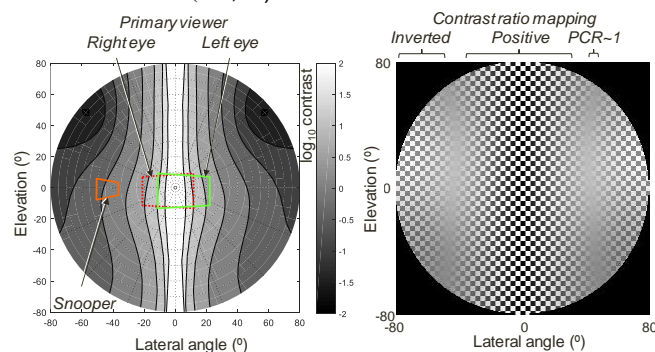


Figure 10. Simulated contrast ratio (left) and appearance (right) for an out-of-plane LC in privacy mode. Display subtended areas for a 14" display viewed at 500mm (primary viewer) and 1000mm (off axis snooper) illustrate variations of image contrast across the display area in both cases.

For a primary viewer, head-on image contrast uniformity is significantly degraded, seen most sensitively as a reduction in colour saturation, and as shown in Figure 11 from a commercially available biased pixel LCD. The contrast is significantly compromised on the right side of the screen for the left eye and on

the left side of the display for the right eye, causing visual stress similar to viewing unbalanced autostereoscopic imagery.

For a snooper, while contrast ratios of 1.0 are achieved over small parts of the image, more typically a contrast ratio of 2 or greater is visible to snoopers on at least some parts of the image and is illustrated by the curve PCR2, PL5% in Figure 4.



Figure 11. Photographs of a bias controlled IPS LCD for appearance to the primary viewer of unbiased mode (above) and biased mode for left and right eyes (below).

5. Conclusion

An analysis of how both contrast and luminance reduction affect privacy display visibility to a snooper under different ambient lighting conditions has been presented. Generally, contrast control privacy displays are more effective at hiding content in low ambient conditions, while luminance controlled privacy displays do better in more common operating environments.

IBT-eQ technology can be configured to use switchable angular luminance or luminance and contrast reduction off axis in order to enable electronically switchable privacy in any ambient lighting environment.

6. References

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