Intelligent Backlight: A controllable illumination system for high efficiency and sunlight readable mobile displays

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Abstract
A novel directional backlight system for transmissive LCD illumination is described for the first time. By controlling the angular light distribution from the display, very low power consumption can be achieved for a required display luminance, or the backlight can operate with a conventional luminance distribution. Additionally very high display luminance can be achieved at the same power consumption levels as conventional backlight designs. Such a display can achieve good readability in high illuminance conditions, for example in direct sunlight. The backlight optical stack comprises a stepped waveguide Directional Light Guide Plate (D-LGP), a micro-structured reflective film and a polarisation recirculation structure that cooperates with an LED array to direct viewing windows to an observer with high coupling efficiency. The system implementation is described and measured performance from demonstrator displays is presented.

1. Introduction
Progress in smartphones and tablets has been driven, at least in part, by the development of high performance transmissive and emissive display technology. The increased display size, pixel resolution, viewing angle and colour gamut have all increased the total luminous flux demand from the display. And displays are commonly required to operate in high illuminance outdoor environments where usability can only be delivered by screen luminance substantially higher than conventionally provided.

Consequently the display has become a major power consuming sub-system, and display efficiency is a limiting factor on mobile device roadmaps.

OLED displays offer relatively high quantum efficiency, although limited luminous emittance with current material systems restricts device lifetime and operation in high illuminance levels. The Lambertian output characteristics of OLED provides limited or no directionality control in contrast to *Intelligent Backlight* technology, described below.

Progress with conventional backlight performance for transmissive LCDs, for example those using standard Light Guide Plates and light control films including ESR™, BEF™ and DBEF™ from 3M Corporation[1] has been augmented by rapid improvements in LED efficiency. However such improvements will now slow as LEDs approach theoretical efficiency limits while the optical stacks also appear to approach the practical limits of optimisation.

2. Directional illumination
Conventional backlights and OLED emitters distribute light into a wide range of angles; thus most light produced by the display is wasted by not being directed to the observer's eyes.

Directional backlights overcome this wastefulness by producing light that is only directed to the observer, as shown in Figs. 1a and 1b.

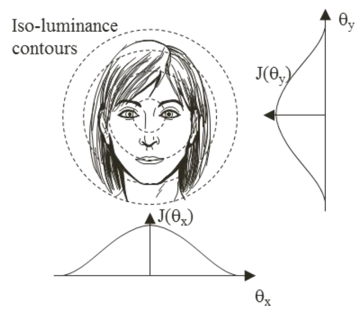

Fig. 1a. Most light in a conventional backlight does not go to the observer's eyes

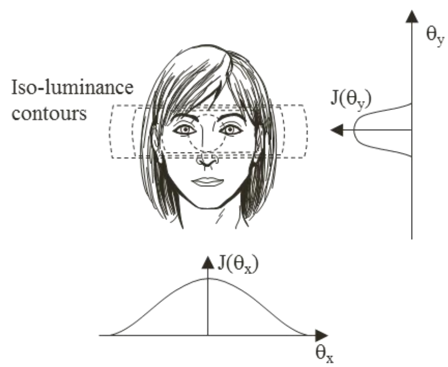

Fig. 1b. Directional backlights increase efficiency by minimising wasted light that is not seen by the observer

Modified conventional backlights are able to reduce their angular distribution of light for example by use of prismatic reflection and diffusing layers[3]. However, the resulting fixed angular luminance distribution fails to provide a conventional wide angle operation when desired by the user.

Wedge illumination[4] may provide directional output by imaging an array of LEDs at a thin input side of a polished wedge to an array of viewing windows. After reflection from a mirrored end with optical power in a first axis and deflection in a second axis, light is output at grazing incidence through the output surface and turning films redirect the light to the observer. Such displays require high precision optical wedges and complex mirror surfaces, both of which can be difficult to produce in the thin optical stacks required of mobile displays.

The *Intelligent Backlight* described below comprises a new optical stack with a stepped bidirectional waveguide, and films arranged to provide polarisation recirculation and luminance gain. Importantly it can be switched between different angular modes to meet the users' varying needs.

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3. *Intelligent Backlight* structure & operation

3.1 Optical stack

A Directional Light Guide Plate (D-LGP) provides the imaging function of the backlight and is shown in Figs. 2a-2b[5,6]. The optical stack further includes a High Brightness Film having a metallised microstructured surface. The light management film comprises a reflective polariser, a retarder arranged to rotate the polarisation state onto the input of the LCD and a low haze diffuser.

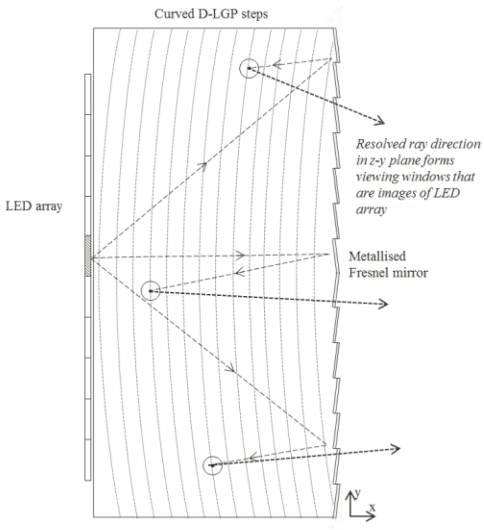

Fig. 2a. Top view of light propagation in D-LGP

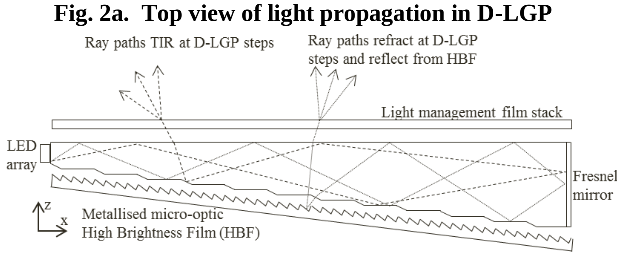

Fig. 2b. Side view of light propagation in the full optical stack of the *Intelligent Backlight*

Light from at least one of the LEDs of the array is coupled into the thin end of the D-LGP and propagates in the x direction while expanding in the y-direction with total internal reflection at the plane surfaces of the guide. The steps of the waveguide are hidden from the propagating beam and importantly, no light is extracted and no loss is present on this first pass from the LED to the mirror. Reflection from the Fresnel mirror at the thicker end of the D-LGP waveguide acts to collimate reflected light, which is guided by the parallel surfaces in the –x direction towards the input end unless it is incident on any of the steps. On incidence with the curved step extraction features the light from each LED is directed out of the waveguide towards a respective viewing window with a limited extent in the yz plane, as shown in Fig. 1b.

At an extraction feature, a portion of the light is internally reflected back into the waveguide and then out towards the LCD. The remainder of the light is transmitted through the light extraction features and on to the High Brightness Film (HBF), from which it is reflected and redirected back though the D-LGP towards the LCD. The light cones from these two paths may be designed to overlap, so that the total luminance for on-axis viewing positions may be substantially increased.

Polarisation recirculation is achieved by reflection of light rejected by the reflective polariser between the D-LGP and the LCD. The recirculated light is retroreflected at the HBF, increasing brightness and angular uniformity in the θ_x axis. Since polarisation recirculation does not involve scattering (as it does for conventional optical stacks), high efficiency is possible. Optimisation of the D-LGP and HBF microstructures can deliver an angular uniformity profile in the xz plane that is similar to a conventional backlight.

The materials and microstructure tolerances of the optical stack are similar to those used in conventional backlights, delivering cost and manufacturability that the authors believe is suitable for the high volumes of the mobile displays industry.

3.2 Hidden fan-out

Bezel size is an important aesthetic of mobile devices making elimination of LED visibility in a small bezel a requirement for any new backlight technology. *Intelligent Backlight* positions the LED array to one side of the D-LGP, but can still deliver very thin bezels by nature of its hidden fan out characteristics as shown in Figs. 3a & 3b.

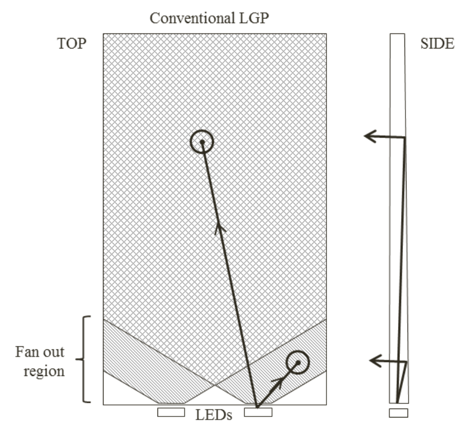

Fig. 3a. Unidirectional ray paths of conventional backlight LGPs needs a large bezel to hide the fan out region

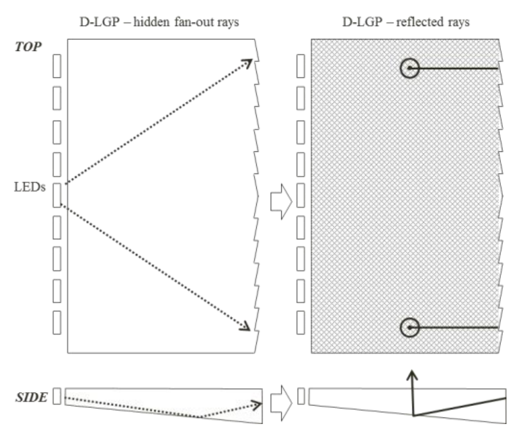

Fig. 3b. Bi-directional ray paths in the D-LGP hide the fan out within the waveguide delivering a very small bezel

3.3 Illumination control

Intelligent Backlight can provide light shaping characteristics that enable programming of angular output depending on user requirements and the illumination environment; for example trading off angular output characteristics with backlight power consumption.

As shown in Fig. 4, by varying the number of LEDs that are switched on, and controlling power distributions, then the luminous intensity distribution can be modified.

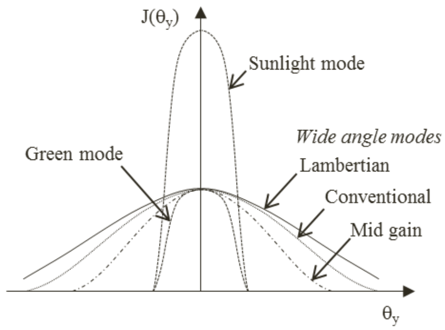

Fig. 4. Varying LED array luminous flux distribution controls luminous intensity distribution

The display output can be dynamically switched between:

Green mode - to increase battery lifetime or reduce battery thickness and weight

Sunlight mode – described below, for daylight and sunlight operation, for example for outdoor photography

Wide angle modes – for multiple viewers, general operation maintaining compatibility with conventional backlights.

Additional modes with different trade-offs can be created, for example between viewing comfort, power savings, and readability in high illuminance environments.

Increasing either power efficiency or peak luminance can be accommodated by reducing the angular viewing freedom. Note however, the display viewing freedom can be effectively recovered by directing the output viewing cone as shown in Fig. 5. The peak luminance can be arranged to follow a Lambertian, rather than high gain profile; achieving a more natural variation of luminous intensity with viewing angle compared with conventional backlights, with the display preserving its luminance, independent of viewing angle.

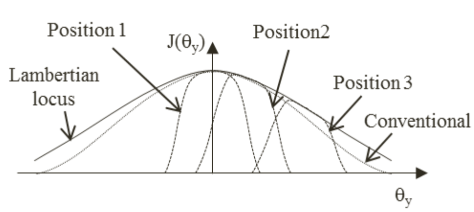

Fig. 5. Varying LED array luminous flux distribution controls luminous intensity distribution

Control of viewing angle can be provided interactively by using the device's touch screen to manipulate the optical output, for instance to drag the high brightness direction towards the user's viewing direction. Head tracking has been used to automate this function.

3.4 High luminance output

The Sunlight mode overcomes the limitations of existing transmissive displays for outdoor use. For the same power consumption as a standard display, the display luminance can be pumped to very high luminance levels, for example to enable use in 25,000lux environments, as explained below.

Evolution of the human visual system has delivered a dynamic contrast ratio that is typically able to adapt to illuminance levels from 10^{-4} lux to 10^{5}lux. The brightness of the environment becomes the reference to which the eye adapts effectively altering the perceived brightness of an emissive or backlit display. Typically displays appear dark and become unusable outdoors.

By modifying the output gamma function of test images, the appearance of displays with various luminance levels can be simulated, as shown in Fig.6. As can be seen the experience of the display 'going dim' when used outdoors is reproduced. High luminance displays can also overwhelm the reflections from front surface, touch screen and pixel plane components of the display panel, further improving image appearance.

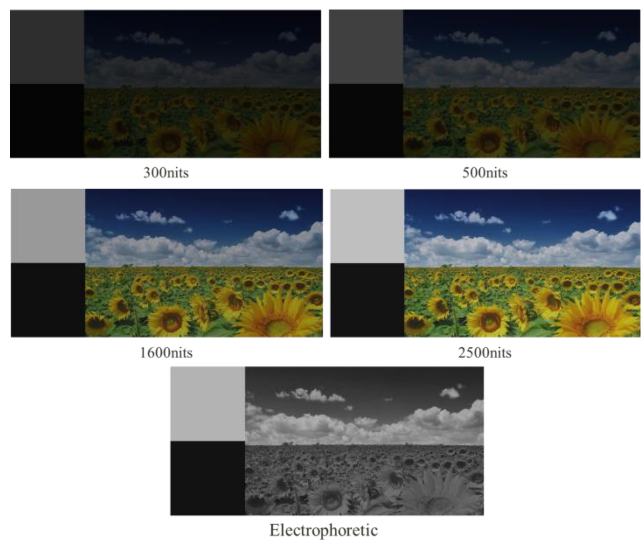

Fig. 6. Simulations of display appearance at 25,000 lux

These results suggest a luminance of 1000nits provides usability at 10klux, 2500nits at 25klux and so on. Such analysis was qualitatively confirmed by the authors at outdoors illuminance levels of 25klux with the technology demonstrator described below.

4. Device fabrication and results

4.1 Technology Demonstrator

A display implementing *Intelligent Backlight* is shown in Fig. 7. Fig.8 shows a demonstration user interface for an LED control API implemented on a Microsoft Surface Pro with a USB interface to a proprietary Evaluation Board. LED grey scale control was provided by a highly integrated LED array drive IC.

Implementations using the 'pinch and zoom' functionality of the device touch screen to control the LED array's settings and to vary the position and size of the output viewing window provided intuitive control of light shaping.

Table 1 shows the parameters of the base display and measured results at the time of writing together with expected results following a series of optimisations.

Fig. 7. ***Intelligent Backlight*** **Technology Demonstrator**

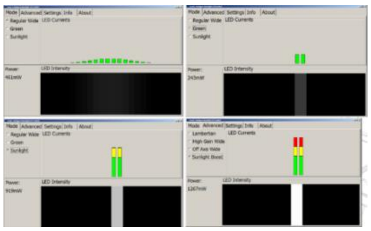

Fig. 8. API implementation in display control interface

Table 1 shows target specification after a series of upgrades to the technology demonstrator. Current performance is around 50% of that which can be achieved by upgrading components including metal coating reflectivity, LED white point and package modification, and integrated D-LGP moulding.

Parameter	**Target specification**
Panel	IPS mode with capacitive touch
Resolution	326ppi
Panel diagonal	3.5”
Number of LEDs	24
Contrast ratio	Same as base panel
Optical stack thickness	Same or less than conventional
Green mode	
Display power	<125mW
Display luminance	500nits
Sunlight mode	
Display power	450mW
Luminance	>1600nits
Wide angle mode	
Display power	450mW
Luminance	>500nits

Table 1. Target specification after planned upgrades

4.2 Characterisation

To characterise the displays from this program so that they deliver uniformity levels that match or exceed current displays, light field measurement tools have been constructed to evaluate both spatial and angular characteristics. Characterisation and optimisation tools developed include *AutoCal* (Fig.9) - an instrument for spatial and angular light field measurements; and *Optivalve* (Fig.10) – a software tool capable of ray tracing the light field, delivering uniformity design.

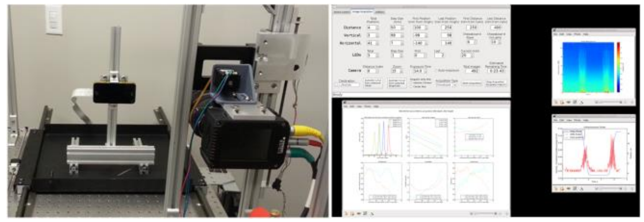

Fig. 9. RealD ***AutoCal*** **light field characterisation instrument with motorised light field measurement & control interface**

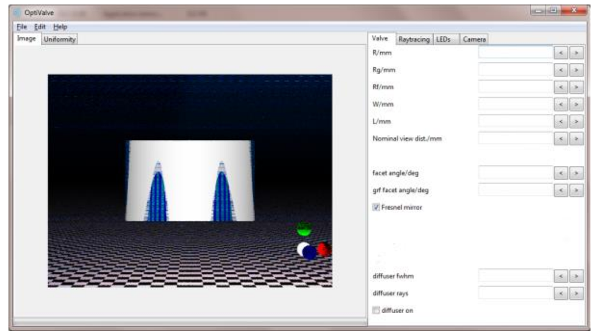

Fig. 10. RealD ***Optivalve*** **uniformity simulator and optical optimisation tool**

5. Conclusion

A novel backlight unit for high volume mobile displays has been developed and demonstrators implemented. The system uses a proprietary optical stack with a novel directional light guide plate in combination with a microstructured film and an addressable LED array. It is compatible with conventional transmissive LCDs and conventional backlight manufacturing. Control of the LED array delivers multiple new functionalities. These include power saving and high luminance for use in very bright outdoor environments (without additional power consumption compared to a conventional backlight). The system can be implemented with a cost that may be the same or better than that offered by conventional 2D backlights while simultaneously achieving high image performance.

6. Acknowledgements

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7. References

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