Design Considerations for LED Backlights
in Large Format Color LCDs

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ABSTRACT
An overview of LED backlight design considerations and alternatives for larger display formats for commercial and avionics applications is provided. Design trades for white & RGB LED lighting will be reviewed, as will thermal considerations and options for controlling luminance and color in typical operating environments.

INTRODUCTION
As the performance of LED devices continues to improve display product developers are looking to replace conventional CCFL backlights in LCD display modules with LED based backlights. While, in many applications the advantages of LEDs makes their use justified, designers and product developers need to take care not to oversimplify the design analyses necessary to ensure design, performance and life goals are achieved.

In developing an LED backlight system for a “large format” LCD module, the design team needs to sort through a plethora of options for devices, opto-mechanical implementation and luminance and color control options. Typical design trades often involve multiple engineering disciplines and affect system complexity. As such, it is necessary to understand and clearly define system requirements early in the design cycle in order to achieve the design goals without excessive design iteration.

This paper will follow a couple of example design developments and step the reader through the typical decision matrix for converging on a design direction. Typical design requirements will be outlined and design trades detailed with the goal of highlighting how such factors as thermal performance and control complexity are impacted by design requirements.

BACKGROUND
LEDs offer numerous advantages and options for backlighting LCD panels. Applications requiring wide color gamut displays will benefit from the saturated primaries available using a mixed RGB LED backlight. Ultra-wide color gamut systems using six color LED backlights have been proposed. Additionally, LEDs offer advantages over hot- and cold-cathode backlights for displays used in environments with wide temperature ranges and high shock and vibration conditions.
LED Benefits

- Low Voltage DC (low EMI)
- High reliability, long-life
- Rapid switching speed
  - Field sequential color & pulsed operation compatible
  - Dimming with PWM
- Area addressing
- Wide color gamut capability (> 100% NTSC)
- Severe environment applications
  - Vibration and shock safe
  - Wide operating temperature range from -40°C to +85°C
  - No heaters for cold temp B/L; Instant ON at all temperatures
- Small packages; Mercury and lead free

While the benefits of LEDs are many, there are still a number of challenges which limit LED applications for LCD backlighting. Product developers need to carefully evaluate the cost, power, thermal and optical design impacts of transitioning to LED backlights.

LED Challenges

- Cost
  - Lumen efficiency (Currently ~1/2 of CCFL)
  - System design complexity
    - Point sources: optical design impact
    - Power supply and controllers
    - Color control w/ RGB systems
  - Performance over temperature
    - Thermal/mechanical design
    - Efficiency roll-off for some colors
    - Color variation for mixed systems

LED Performance Roadmaps

The lumen efficiency of LED backlight systems is driven by device level efficiencies and backlight optical designs. Optical system efficiencies of the various LED backlights designs are comparable to their edge-lit and direct-view fluorescent backlight counterparts. Some minor transfer losses may be incurred in RGB based designs due to the added mixing components.
Since LED device efficiencies have been the focus of intense development in recent years, improvement trends promise to bring LED device efficiencies in line with those of CCFL in the very near future. For example, a generally accepted photometric efficiency for CCFL lamps used in LCD backlighting is around 60 – 65 lumens per watt at their optimal temperature. Present commercially available packaged LEDs are achieving upwards of 40 – 50 lumens per watt and projections are being made for 75 – 100 lumen per watt components in the next few years.

While this is great news for the backlight designer, we still need to take care to understand the performance of these new devices in our products over the full operational environment. A brief example will highlight this concern relative to operation in a product at elevated temperature.

**BACKLIGHT SYSTEM DESIGN CONSIDERATIONS**

**A Brief Example**

Let’s consider an LCD backlight design for a critical application with a high operation temperature environment. A more detailed analysis of a specific backlight designs follows in later sections, but for now a quick back of the envelope calculation will highlight the concerns a designer should consider. Assume a high operating temperature requirement for a display product of 65°C which is not uncommon in many mobile display applications. Assuming an efficient thermal design we allow for at least a 15°C internal air temperature rise. Thus the backlight is operating in an 80-90°C internal ambient. As the graph below shows, a CCFL backlight has a roll-off in efficacy as the temperature of the lamp cavity exceeds the optimal (~50-60°C). With the lamp wall at 90-100°C the efficacy drops to around 75% of the optimal or roughly 49 L/W.

Consider now an LED backlight in the same display and same environment. A B/L design might use discrete RGB, high flux power LEDs such as the Lumileds Emitter with approximately 1.0 watt power dissipation per device. For the typical 27%, 65%, 8% RGB mix, the lumen efficacy at 25°C LED junction temperature would be roughly 28 L/W. It is easy to show that the junction temperature in the 65°C ambient (80°C internal ambient) could easily rise to 120°C.

In this case, the light output of the LEDs degrades significantly for red and green resulting in an operational lumen efficacy of less than 16 L/W or roughly a third of that of the CCFL backlight.
While this example highlights a severe condition, many displays are required to continue to operate in ambient temperatures exceeding 70°C. As such, the thermal design of the backlight and selection of the illumination scheme, heat-sink, active cooling options and color and luminance control become crucial. The remainder of this paper will focus on the design process technical trades associated with providing a reliable and efficient LED backlight system for larger display sizes.

**LED Backlight Design Process**

The goal of any display product development is to design a product that meets or exceeds cost and performance goals in as short a time as possible with minimal iterative effort and prototyping. As such, it is important to clearly define the overall system requirements before beginning the design. The block diagram below highlights key design requirements which must be defined in the early development stages: environmental, display, electrical, optical and mechanical requirements. Typical performance parameters and constraints are listed below the blocks. After basic product requirements are defined, two processes may be followed to define the backlight requirements and initiate a concept design. The “baseline and modify” approach may be used when an existing display is to be modified to an LED backlight. Here the performance of the existing display with, for instance, a CCFL backlight is measured and LED design estimates are made based on the CCFL flux-to-display luminance ratios. A second approach measures LCD transmission (spectrally if possible) and models the flux requirements based on spectral transmission of the LCD and estimated backlight throughput efficiencies.

Factors affecting the backlight design path include:

(a) Flux Requirements: Is the requirement for standard (~300 cd/m²), high brightness (450-600 cd/m²), or ultra-high brightness (>750 cd/m²)? An edge-light design should work for the standard brightness and possibly the high brightness display (if not too large), but a direct-view design will be required for the ultra-high brightness display.

(b) Weight: Edge-light type designs become heavy and less efficient as the size grows. While a direct-view design will be slightly thicker than a design incorporating a light-guide, it will be lighter and cheaper in the larger sizes. Several direct view designs have been shown using high flux LEDs such as the Lumileds Luxeon emitters and Osram Golden dragon devices.
(c) Color Gamut: LED backlit LCDs with color gamuts exceeding 100% of NTSC have been demonstrated using mixed RGB LED backlights. However, it is possible to achieve comparable color gamuts to CCFL backlit LCDs using phosphor converted white LEDs. The designer should perform a detailed design trade study to weigh the cost, complexity and board area requirements of a wide color gamut backlight against that of the simpler white LED design which requires 1/3 the number of drivers, simpler control (T feedback only), simpler PCB layout, no optical mixing elements, etc.

LED Device Selection – Power Density

LED devices for backlighting can be roughly divided into two categories: standard flux and high flux. Standard flux LEDs are available in a variety of standard leaded and surface mount configurations with power dissipations on the order of 60 -100mW. These devices can be used in a large quantity to generate outputs in excess of several hundred lumens. A typical example of this approach is shown below. These lower power devices tend to use plastic packages and depend on device leads to carry heat to the PCB and therefore are not well suited to high power density, high temperature applications.

High flux LEDs incorporating single high current LEDs or multiple standard current LEDs on highly conductive substrates allow extremely high flux densities by providing lower resistance thermal paths from the LED die to the case or board. Devices such as the Lumileds Luxeon Emitters and Osram Golden Dragon utilize a built-in heatsink which creates a link from the LED die to the PCB. Lamina Ceramics uses a metal clad ceramic substrate to directly mount the LED die to the heatsink thereby allow power levels in excess of 5 watts or more per package. While these approaches are very attractive from a parts count and $/lumen standpoint, the difficulties associated with optically integrating the intense light and dissipating the localized heat energy are considerable.

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1 See for example Lamina Ceramics BL2000 data sheet.
Of particular concern to the designer should be the junction-to-case thermal resistance ($R_{j-c}$) of the LED device. The Luxeon Emitter $R_{j-c}$ is 13-15°C/W, the Golden Dragon $R_{j-c}$ is 9°C/W, and the Lamina BL2000 $R_{j-c}$ is 2.6°C/W. As power densities rise, it is imperative to minimize $R_{j-c}$ since a 3 watt part with a 10°C/W $R_{j-c}$ will see a junction temperature rise of 30°C above the board temperature. In a high ambient temperature environment, the resulting junction temperature will force a power and luminance reduction to maintain device reliability.

LED Device Selection – Color Choices

Several options exist for generating white light in an LED backlight. As mentioned earlier, the designer must decide what color gamut and white point color temperature is required to meet the product requirements and if active backlight color control is desired. If so, and RGB design will be required. If not, an array of options exists in the phosphor converted LED arena thereby making this a viable option for many designs. The figures below depict the spectral content of various white and RGB LED devices.

Note that the Blue-Yellow device phosphor produces a white which is lacking a saturated red component. This will affect the color rendering at the LCD level reducing the color gamut and leaving some scenes looking unnatural. However, this is a very efficient device design and can be used in numerous applications where life-like color is not required.
By either adding a red phosphor component or, in a multi-die package adding a red LED, the color saturation of the red can be greatly improved. This provides a viable solution when active backlight color mixing is not required. Finally, Toyoda Gosei\(^2\) has developed a device using tri-band phosphors excited by a purple (near UV) LED to give a high color rendering index in a part with excellent color uniformity in a very small package. However, since the purple component does not contribute to the luminous efficiency, this device is lower on the efficacy scale than the Blue-Yellow devices and therefore best suited to standard luminance backlight designs.

**Color Gamut and Color Control**

As the graphs above highlight, the output of the LEDs in an RGB LED backlight varies along different temperature curves. Notice that the output of the InGaN based blue LEDs varies much less than the AlInGaP red and amber LEDs. This impacts both the white point of the backlight and color gamut of the LCD necessitating some form of control circuit. Optical (luminance or color) and temperature sensor based circuits have been proposed.\(^3\) System complexity grows as the allowable chromaticity shift over temperature is reduced. Color shift over the dimming range is also an issue for displays with wide-range dimming. A significant amount of work has been done to characterize the impact on color constancy of the various dimming schemes using PWM or constant current dimming.\(^4\)

It is worth noting that, since most phosphor converted white LEDs use a blue InGaN LED as the pump for the phosphor, the change in flux and color with temperature is much less with a phosphor converted white LED B/L than with an RGB design. The sacrifice in color gamut may be offset by the simpler circuit design if the product requirements do not necessitate an ultra-wide color gamut. This is especially true if an LED backlight is being proposed for an LCD backlight where the existing product’s color range is sufficient though it may only be 45-60% NTSC with the CCFL.

**Thermal Considerations**

Determination of LED junction temperature under normal and high temperature operating conditions is key to determining the reliability of the backlight design and capability of the system to provide the desired luminance and color over the full operating range. A simplified thermal analysis should be performed after initial design concepts are developed to ensure that maximum junction temperatures are not exceeded.

In modeling the thermal characteristics of the backlight system a resistor network model may be used. A typical network analysis is depicted below where \(T_J\) and \(T_a\) are the LED junction and ambient temperatures, respectively. The goal is to determine the junction temperature based on a known ambient temperature, LED power dissipation, and component thermal resistances. The first

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\(^2\) See for example Toyoda Gosei SMD top view part E1S40_1W0C6_01.


step is to map the thermal path in terms of series and parallel thermal resistances. The resistor network can then be simplified to an equivalent circuit with a single resistance representing the combined junction-to-ambient thermal resistance as shown below. When this is done then the junction temperature can be determined from

\[
T_J = T_a + P \left( R_{j-a} \right)
\]

The thermal resistance consists of three or four resistors in a series parallel arrangement as shown:

- \(R_{j-c}\) - Thermal resistance from die to the component case.
- \(R_{c-b}\) - Thermal resistance from component case to PCB.
- \(R_{b-s}\) - Thermal resistance from PCB to heatsink (includes PCB thermal R).
- \(R_{s-a}\) - Thermal resistance from the heatsink to the ambient air.

Clearly, the primary task of the designer is to reduce the value of \(R_{j-a}\) to a minimum by careful design and component selection including LEDs, PCB, heatsink and cooling paths (air flow, case cooling, etc.). An essential component in the design of a high power LED backlight is the PCB. It is strongly recommended that metal clad printed circuit boards\(^5\) be incorporated and that appropriate thermal vias be used to ensure that \(R_{b-s}\) is minimized. Heatsinks can then be selected or designed such that \(R_{s-a}\) is minimized within the system envelope allowances.\(^6\) Note that it might be necessary to use forced-air cooling to lower \(R_{s-a}\) and thereby achieve the junction temperature requirements of the LED manufacturer.

**BACKLIGHT DESIGN ANALYSIS**

The following examples will help to outline the process for evaluating the thermal and luminance performance of an LED backlight over temperature.

The first example is a 10.4” LCD which previously used dual CCFLs to produce 350cd/m\(^2\) white luminance. The flux from the CCFLs is approximately 325 lumens. The proposed design seeks \(>600\) cd/m\(^2\) luminance so we will need around 700 lumens. The proposal is to use an array of discrete RGB Luxeon emitters and a mixing light guide as suggested on the Lumileds website. In this case a high brightness backlight is desired so two rows of LEDs are mounted to a single MCPCB as shown in the figures. While two different configurations are depicted, let’s assume that 24 Luxeon I devices are mounted to the PCB and that they will be run at \(~1.1\)W each so the total power dissipated \(~26\)W. While not shown in the models, a finned heatsink was selected in order to keep

\(^{5}\) See for instance Berquist Company for info on MCPCB.

\(^{6}\) See Aavid Thermalloy for a nice extruded profile heatsink design tool.
the junction temperature at around 110°C in a 50°C ambient. The table below summarizes the thermal calculations.

Note that at this junction temperature, the combined output of the RGB LEDs would be roughly 59% of the rated flux so the backlight will likely not meet its design target luminance at the elevated ambient temperature. If active cooling is applied, the heatsink resistance could be brought down to 0.25°C/W and the junction temperature would fall to around 96°C where the flux is 65% of rated.

<table>
<thead>
<tr>
<th>LED Qty in B/L</th>
<th>24</th>
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</thead>
<tbody>
<tr>
<td>Power per LED</td>
<td>1.1 W</td>
</tr>
<tr>
<td>$R_{J-C}$</td>
<td>14.00°C/W</td>
</tr>
<tr>
<td>$R_{C-B}$</td>
<td>0.06°C/W</td>
</tr>
<tr>
<td>$R_{B-S}$</td>
<td>1.00°C/W</td>
</tr>
<tr>
<td>$R_{S-A}$</td>
<td>0.81°C/W</td>
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</table>

<table>
<thead>
<tr>
<th>Assumed Ambient T</th>
<th>50°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Derate Factor</td>
<td>100%</td>
</tr>
<tr>
<td>Total LED Power</td>
<td>29.4 W</td>
</tr>
<tr>
<td>LED Heat Flux (=0.85*Ptot)</td>
<td>24.99 W</td>
</tr>
<tr>
<td>Net Thermal Resistance</td>
<td>2.44°C/W</td>
</tr>
<tr>
<td>Junction T</td>
<td>110.9°C</td>
</tr>
</tbody>
</table>

The second example uses a white LED array on a metal clad ceramic substrate as the source in a direct view design. Let’s calculate the junction temperature based on the same power dissipation as above (~29W). In this case, since the LED substrate contacts directly the heatsink, there is no $R_{b-s}$ and the net thermal resistance comes down to 1.03° C/W. The resulting junction temperature is ~75°C. Since the luminance of the phosphor converted white LED roughly follows the temperature curve of the InGaN blue LED, the luminance of this design configuration can be expected to maintain >85% of its design value at 50°C.

<table>
<thead>
<tr>
<th>LED Qty in B/L</th>
<th>12</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power per LED</td>
<td>5 W</td>
</tr>
<tr>
<td>$R_{J-C}$</td>
<td>2.60°C/W</td>
</tr>
<tr>
<td>$R_{C-B}$</td>
<td>0.08°C/W</td>
</tr>
<tr>
<td>$R_{B-S}$</td>
<td>1.00°C/W</td>
</tr>
<tr>
<td>$R_{S-A}$</td>
<td>0.81°C/W</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Assumed Ambient T</th>
<th>50°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Derate Factor</td>
<td>52%</td>
</tr>
<tr>
<td>Total LED Power</td>
<td>29.4 W</td>
</tr>
<tr>
<td>LED Heat Flux (=0.85*Ptot)</td>
<td>24.95 W</td>
</tr>
<tr>
<td>Net Thermal Resistance</td>
<td>1.03°C/W</td>
</tr>
<tr>
<td>Junction T</td>
<td>75.6°C</td>
</tr>
</tbody>
</table>

$R_{s-a} = 0.81°C/W$
SUMMARY AND CONCLUSIONS

When considering what type of backlight system to use, consideration should be given to the key characteristics that define the system performance objectives such as color gamut, luminance, package size, and operating environment. In many cases, competing objectives, such as optical performance and cost, or hot ambient operating temperature performance, must be balanced against other objectives. It is essential to perform analyses of operation in the installed environment to ensure design targets using room ambient data will hold at elevated temperatures. The thermal design of the backlight must be carefully evaluated and tested to make certain LED junction temperatures remain within the allowable range for high reliability operation.

AKNOWLEDGEMENTS

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