LUMILEDS

For LCD Backlighting
Luxeon DCC

Introduction

This Application Note provides the information that is needed to develop a backlight system with Luxeon® DCC and includes reference designs that explain the concepts.

Luxeon DCC is an energy efficient and ultra compact light source that combines long life, robustness, and reliability of light emitting diodes (LEDs) with the luminance of conventional lighting.

When used as the light source for a liquid crystal display (LCD) backlight, Luxeon DCC light sources offer dramatic advantages over conventional lighting and other market place LED solutions.

The following illustration shows a design method for a backlight assembly using a Luxeon DCC light source concept called the Folded Mixing Light guide Concept (FMLG).
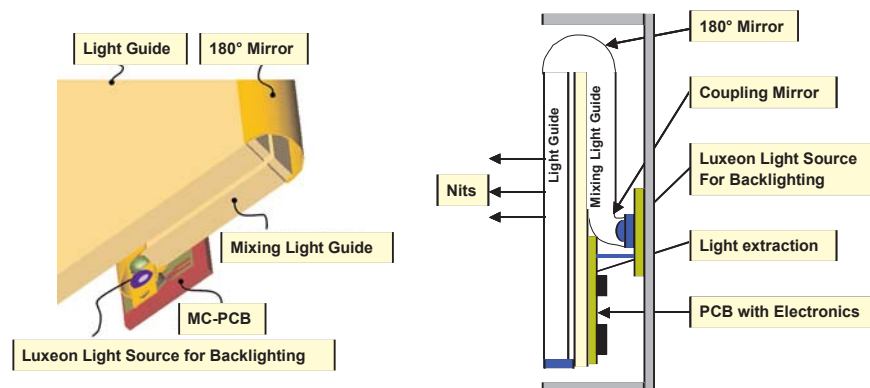

Figure 1. Folded Mixing Light Guide Concept (FMLG)

Application of Luxeon DCC as a light source for LCD backlights requires partial redesign of the optical, thermal and electrical components of the LCD backlight.

Key Benefits

- Vivid color saturation of images on the LCD display
- Reduced motion artifacts through fast switching LED technology
- Optimized color and white point settings for DVD and computer applications
- Backlight panel consistency
- Full gray scale with real-time dynamic luminance control
- Robust design for automotive, industrial/medical, avionics and military applications
- Environmentally friendly products do not contain any mercury

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Chapter 1: General Principles of RGB Light Mixing

Luxeon DCC for LCD backlighting mixes light emitted by red, green, and blue LEDs to create a white light that is coupled into a backlight. This section describes the following aspects of RGB color mixing:

- Color spaces
  including concepts such as dominant wavelength, correlated color temperature (CCT) and backlight requirements
- Color gamuts
- Addition of colors, including the calculation rules for the translation from luminance and color specifications of white light into the corresponding data of the RGB colors, and vice versa

1.1 Color Spaces

One of the most fundamental properties of light is its color spectrum, which defines the optical power density of light as a function of its wavelength. All color spectra that can be detected by the human eye can be represented in a number of different, three-dimensional spaces.

To convert a spectrum to a color space, the color matching functions of the International Commission on Illumination (CIE) standard colorimetric observer functions are used in Figure 1.1. These functions describe the sensitivity of the human eye per wavelength over the whole visible spectrum.

One of the most common conversions splits it into:

- Two variables for color
- One for luminance

For color representation only two dimensions are sufficient and the luminance is often omitted. This reduces the color space into a two dimensional space.
The most common 2-dimensional color spaces used are:

- CIE 1931 xy Chromaticity Space
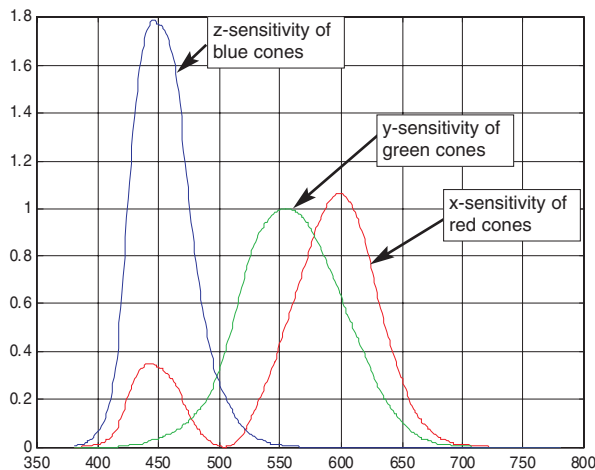- CIE 1976 UCS (Uniform Color Space) Chromaticity Space

Figure 1.1. CIE 1931 Standard Colorimetric Observer sensitivity curves for red (x), green (y) and blue (z) cones

The details of the conversion from a 3-dimensional color spectrum into a two-dimensional representation are beyond the scope of this Application Note and can be found in Chapter 1.4, References 1 and 2.

1.1.1 Two-dimensional Color Space Representations

The basic two-dimensional representation of visible color is the CIE 1931 xy Chromaticity Space as shown in Figure 1.2. This is the most commonly used two-dimensional color representation. It has one major drawback, as the distance between two points in this space (Δxy) does not correspond with the perceived color difference.

In the more advanced CIE 1976 UCS Chromaticity Space this drawback has been resolved to a large extent. See the second representation in Figure 1.2. Although still not perfect, this diagram is the preferred two-dimensional color representation. In this second space the distance between two points, usually called Δu'v', is a useful indication of the perception of color difference. A typical value for the visibility limit is Δu'v'=0.005.
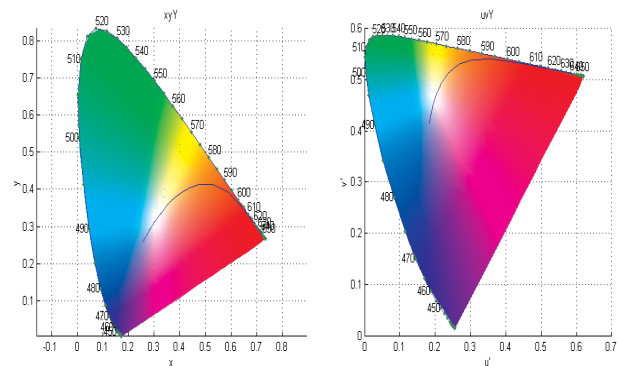

Figure 1.2. The CIE1931 xy Chromaticity Space (Left) and the CIE1976 UCS u'v' Chromaticity Space (Right)

Color Uniformity of a Backlight

The color uniformity of a backlight can be determined on the basis of a central reference point (usually the center of the backlight) with color coordinates u'_{center} v'_{center}. By measuring the color point at any location on the backlight, the difference in color can be calculated using Formula 1.1

$$\Delta u'v' = \sqrt{(u' - u'_{center})^2 + (v' - v'_{center})^2} \qquad \textbf{Formula 1.1}$$

The maximum value of Δu'v' anywhere on the display provides an indication of the quality level of the color uniformity

1.1.2 Dominant Wavelength

In addition to chromaticity coordinates, an LED is frequently specified in terms of its wavelength. Instead of the peak wavelength, i.e. the wavelength where the radiometric spectrum reaches its maximum, the dominant wavelength is often used.

Dominant wavelength is used because the dominant wavelength represents the best level of correspondence with the color perceived by the human eye. The dominant wavelength can be determined in the u'v' (or xy) diagram by drawing a line from the Illuminant E, the Equal Energy White-point (EEW), to the xy-point of the LED, and extending this line to the spectrum locus. The intersection of this line with the spectrum locus closest to the LED point defines the dominant wavelength. See Figure 1.3, and refer to Chapter 1.4, Reference 4.
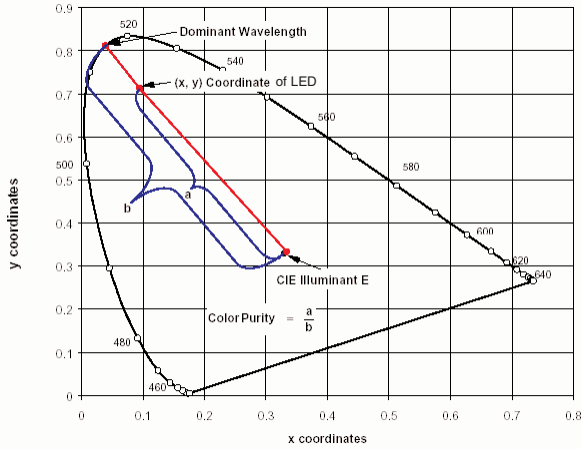

Figure 1.3 Graphical Determination of Dominant Wavelength

Note: The Equal Energy White (EEW) point is equal to Illuminant E, where (x, y) = (0.3333, 0.3333) or (u', v') = (0.2105, 0.4737).

1.1.3 Correlated Color Temperature (CCT)

The line in a chromaticity diagram that connects all points that represent the chromaticities of a black body radiator at different temperatures is called the black body locus. See Figure 1.4.

A chromaticity point on the black body locus can also be expressed in terms of degrees Kelvin, i.e. the measured temperature of the black body. Black body radiators emit specific colors at specific temperatures. Therefore a point on the black body curve is commonly referred to as a color temperature. Yellowish white light has a lower color temperature than bluish white light (in contradiction with the perception by the human eye, where yellow white light is considered to be "warmer" than blue white light).

Chromaticity points of white light sources that do not lie on the black body locus are defined in terms of a Correlated Color Temperature (CCT). If the chromaticity points do not lie on the black body locus, then this color temperature correlates to the color temperature of a chromaticity that lies on the black body curve and that has the shortest distance from the black body locus to the point that is not on the black body locus in the 1960 u'v' chromaticity diagram, i.e. the normal to 1960 locus. See Figure 1.4, and refer to Chapter 1.4, Reference 4.
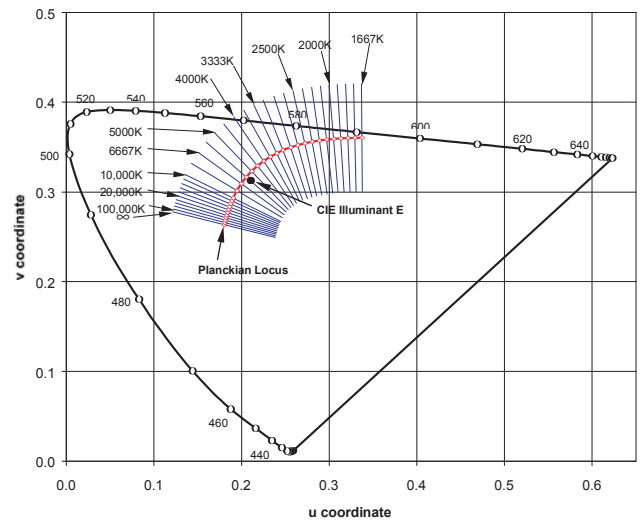
Figure 1.4 a) CIE-1960 uv-diagram with isothermal lines (CCT) perpendicular to the black body locus
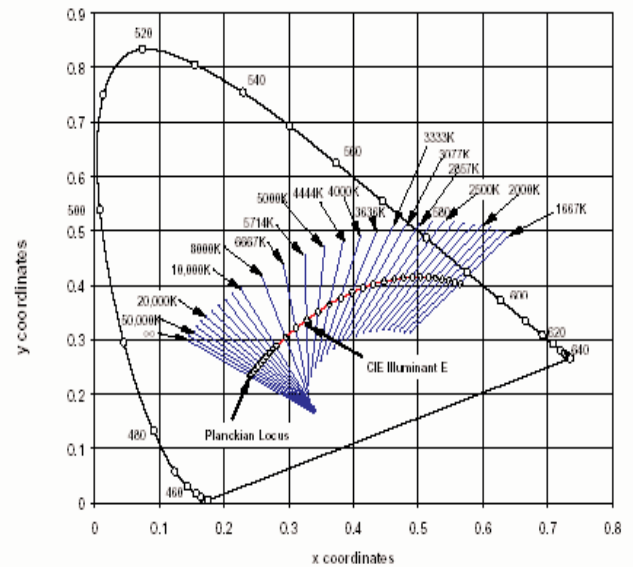
Figure 1.4 b) CIE-1931 xy-diagram with Isothermal Lines (CCT) and Black Body Locus

The correlated color temperature can be calculated on the basis of the values for x and y and a table with correlated temperatures.
Note: the correlated color temperature is only useful for colors near the black body locus.

1.2 Color Gamuts

The color performance of television sets and computer monitors is strongly influenced by the color gamut. The color gamut represents the total set of colors that can be produced by the display. All current displays use the three color-channels red, green and blue, the primary colors of light.

A color point in the xy or u'v' diagram can represent each of the three primary colors. When all three primary colors are

driven in a specific mix, white is obtained. The triangle of the three primary colors, including this white point, is called the color gamut.

In theory the display can produce all colors that are inside this color gamut. The maximum luminance that can be produced is not the same for each color. In general the maximum luminance is close to the white point, and will decrease towards the borders of the triangle. The diagrams in Figure 1.2 represent the contour of all colors that are visible for the human eye. Because of the curved shape of this contour it is not possible to define a triangle with visible primaries that covers all visible colors.

Historically a number of standard gamuts have been defined for displays, and initially these were mainly based on the Cathode Ray Tube (CRT) phosphors available at that time. The first gamuts were National Television System Committee (NTSC) and European Broadcasting Union (EBU). See Figure 1.5. These are still widely used for television transmissions and video recordings.
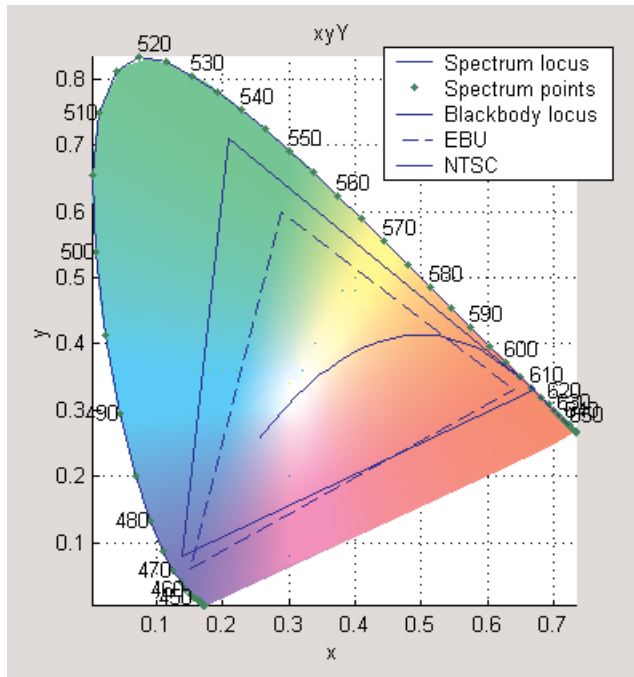

Figure 1.5   NTSC and EBU Gamut

In Table 1.1 the exact corner points of the EBU and NTSC triangle are given as well as the flux ratios per color to achieve for example the 9000K-point (a common CCT for LCD backlights. When using LEDs with different xy-coordinates this flux ratio will change as described in Chapter 1.3.

Table 1.1 Color Gamut Points and Flux Requirements per RGB Color

Gamut Corner Points	NTSC			EBU		
	x coord	y coord	Flux required to generate a CCT of 9000 K (%)	x coord.	y coord.	Flux required to generate a CCT of 9000 K(%)
Red	0,670	0,330	27,3	0,640	0,330	20,1
Green	0,210	0,710	58,9	0,290	0,600	70,2
Blue	0,140	0,080	13,8	0,150	0,060	9,6

Note: 9000 K is at x=0,287 and y=0,296 in the 1931 CIE Chromaticity Diagram

1.3 Addition of Colors

In perceiving red, green, and blue, the retinal cones in the human eye give off three signals: X, Y and a Z value, also called the tristimulus values. In doing so the green retinal cones actually deliver two signals; one signal for the color, and another signal for the luminance of the light. The result of this phenomenon is that every color sensation consists of four signals:
• X signal: red color
• Y signal: green color
• Z signal: blue color
• Y signal: luminance

The combination of these four signals can be used to describe the perceived color as well as the perceived luminance. Each X, Y and Z value for color is determined by two components: the wavelength of the light source and the sensitivity of a standard human eye for that wavelength. See Figure 1.1. The tristimulus values can be recalculated if the x and y coordinates and the luminance (Y) of a color are known, using Formulas 1.2, 1.3, and 1.4.

$$X_i = \frac{x_i}{y_i} \bullet Y_i$$ **Formula 1.2**

$$Y_i = Y_i$$ **Formula 1.3**

$$Z_i = \frac{1-x_i-y_i}{y_i} \bullet Y_i$$ **Formula 1.4**

Tristimulus values for a color located at x_i and y_i with a luminance Y_i Where i = r(red), g(green) or b(blue)

The general rule in mixing colors is that the parameters of the resulting color are represented by the addition of the X, Y and Z values of the separate colors.

The resulting X, Y and Z of a mix can then be converted to the accompanying x and y values. For more details refer to Chapter 1.4 Reference 3.

1.3.1 Translation from RGB Colors to White

RGB colors have the following, known parameters: xy coordinates and luminance, i.e. (x_R, y_R, Y_R), (x_G, y_G, Y_G) and (x_B, y_B, Y_B). The tristimulus values for each color can be calculated by means of Formulas 1.2, 1.3, and 1.4, which results in separate tristimulus values X_i, Y_i and Z_i for each color. These tristimulus values of the three colors can then be added by means of the following Formulas 1.5, 1.6, and 1.7.

$$X_{white} = X_R + X_G + X_B \qquad \text{Formula 1.5}$$

$$Y_{white} = Y_R + Y_G + Y_B \qquad \text{Formula 1.6}$$

$$Z_{white} = Z_R + Z_G + Z_B \qquad \text{Formula 1.7}$$

The x and y coordinates for the white light can now be calculated by means of Formulas 1.8 and 1.9.

$$x_{white} = \frac{X_{white}}{X_{white} + Y_{white} + Z_{white}} \qquad \text{Formula 1.8}$$

$$y_{white} = \frac{Y_{white}}{X_{white} + Y_{white} + Z_{white}} \qquad \text{Formula 1.9}$$

Combined into a matrix, the transition from RGB into white light can be expressed as follows:

Formula 1.10

$$\begin{pmatrix} X_{white} \\ Y_{white} \\ Z_{white} \end{pmatrix} = \begin{pmatrix} \dfrac{x_R}{y_R} & \dfrac{x_G}{y_G} & \dfrac{x_B}{y_B} \\ 1 & 1 & 1 \\ \dfrac{1-x_R-y_R}{y_R} & \dfrac{1-x_G-y_G}{y_G} & \dfrac{1-x_B-y_B}{y_B} \end{pmatrix} \bullet \begin{pmatrix} Y_R \\ Y_G \\ Y_B \end{pmatrix}$$

1.3.2 Translation from White to RGB

The luminance Y and the xy coordinates for white, i.e. for a backlight, are usually specified in the product specification. This chapter describes a method to calculate the required flux per given red, green and blue color, that when mixed results in the required luminance Y and xy coordinates for white. The given luminance Y_{white} and its color coordinates x_{white} and z_{white} may be inserted in formula 1.8 and 1.9 and then the values X_{white} and Z_{white} can be derived via rearrangement and substitution. Then the inverse of Formula 1.10, Formula 1.11 calculates the required luminance of the given RGB colors:

Formula 1.11

$$\begin{pmatrix} Y_R \\ Y_G \\ Y_B \end{pmatrix} = \begin{pmatrix} \dfrac{x_R}{y_R} & \dfrac{x_G}{y_G} & \dfrac{x_B}{y_B} \\ 1 & 1 & 1 \\ \dfrac{1-x_R-y_R}{y_R} & \dfrac{1-x_G-y_G}{y_G} & \dfrac{1-x_B-y_B}{y_B} \end{pmatrix}^{-1} \bullet \begin{pmatrix} X_{white} \\ Y_{white} \\ Z_{white} \end{pmatrix}$$

Annex B of this Application Note shows a sample calculation.

1.4 Reference Information

1. The IESNA Lighting Handbook, ISBN 0-87995-150-8.
2. Publication CIE No 15.2, ISBN 3 900 734 00 3 / ISBN 931 7251 59 6 CIE Vienna, Austria
3. Daniel Malacara, Color vision and colorimetry - Theory and applications, ISBN 0 8194 - 4228-3; chapter 6 Color mixtures and colorants.
4. AB08, Optical Testing for SuperFlux, SnapLED and Luxeon Emitters. See www.lumileds.com.
5. High Brightness Light Emitting Diodes by Stringfellow and Craford, ISBN 0-12-752156-9.
6. Introduction to Solid State Lighting, by Zukauskas, Shur and Gaska publ. John Wiley & Sons, ISBN 0-471-21574-0.

Chapter 2: Light Source Requirement Analysis

This chapter describes a methodology for determining the requirements for a Luxeon DCC light source. The described calculation method is divided into 5 logical steps and is illustrated with a sample calculation for a 15" monitor used throughout this application note. The methodology can be used for all screen sizes. Adapting the input values and monitor parameters of other specifications allow the selection of a Luxeon DCC light source appropriate for other screen sizes
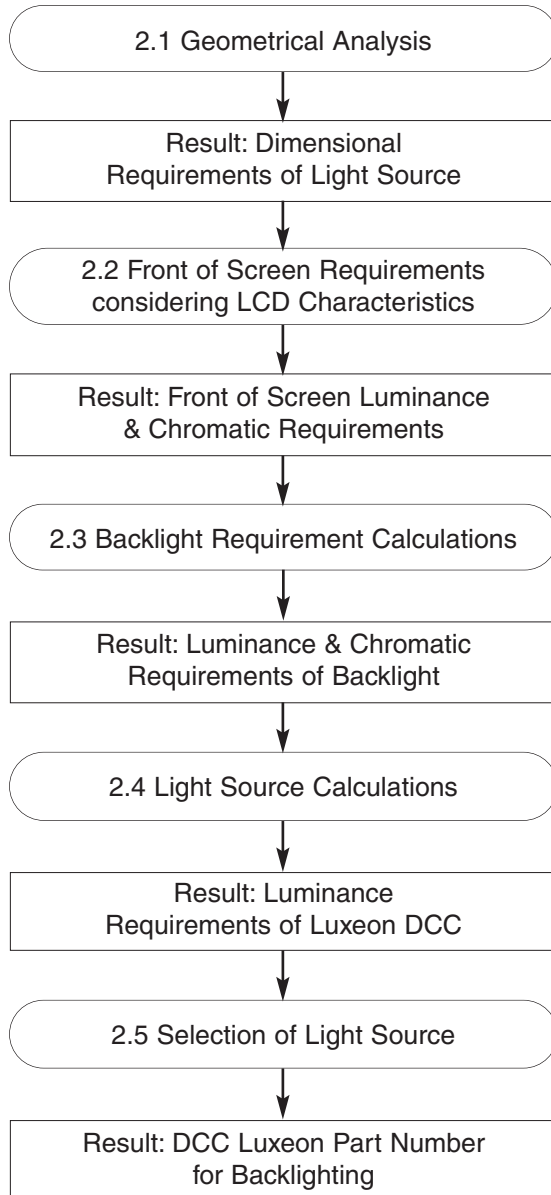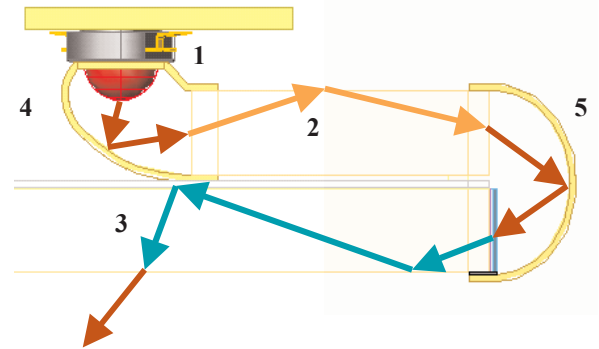

Figure 2.1 Sequence of calculations required for determining the correct Luxeon DCC Light Source for the screen size in question.

2.0 General Building Blocks of a Backlight

1. Luxeon DCC Light Source
2. Mixing Light Guide
3. Main Light Guide
4. 90° Coupling Mirror
5. 180° Coupling Mirror

2.1 Geometry of the LCD Display (Step 1)

The first step of the light source selection and specification process is to determine the dimensional requirements from the screen size. The length of a LED light source should be equal to the height or width of the display. A deviation of plus or minus 5mm is acceptable. Figure 2.2 and Table 2.1 show the height and width calculated with standard goniometric formulas such as

$$L_c = \sqrt{L_a{}^2 + L_b{}^2}$$

for a diagonal screen of 15.0'' and an aspect ratio of 1.33.

Table 2.2 shows the lengths of available Luxeon DCC light sources.

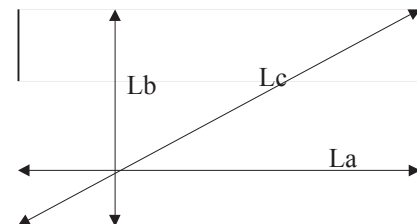**Figure 2.2 Geometry of LCD Display**

Note: It is assumed that diagonal Lc and the aspect ratio of La/Lb is given.

Table 2.1 Example of Dimensions for a 15" Display

Dimension	Symbol	Unit	Value
Diagonal (inch)	Lc	inch	15.0"
Aspect ratio	La/Lb	-	1.33
Diagonal	Lc	mm	381
Height	Lb	mm	229
Width	La	mm	305
Area	A	m^2	0.07

Table 2.2 Overview of the Length of Luxeon DCC Light Sources

Available Luxeon DCC Light Sources	LXHL-MGAA	LXHL-MGBA	LXHL-MGCA	LXHL-MGDA	LXHL-MGEA
Length (in mm)	99	153	225	306	360

Light source LXHL MGDA has a length (306mm) that is close to La for a 15" display, see Table 2.1, and thus is recommended for this display size. Alternatively, light source LXHL MGCA has a length that is close to Lb and can be applied in the height direction of the display.

Summarized, the results of this step are: Best match for the height of the display is LXHL-MGCA (225mm). Best match for the width of the display is LXHL-MGDA (306mm).

2.2 Front of Screen (FOS) Requirements and LCD Characteristics (Step 2)

The goal of the second step is to determine the display requirements specified by the customer that are needed for light source selection. The requirements for a typical 15" LCD display are shown below in Table 2.3.

Table 2.3 Display requirements for 15" example

Dimension	Symbol	Unit	Value
Color Temp	$\theta_{CCTwFOS}$	K	9000
	white x ($x_{w,FOS}$)	-	0.287
	white y ($y_{w,FOS}$)	-	0.296
Color shift backlight x	Δx_w	-	0.001
Color shift backlight y	Δy_w	-	0.001
Transmission rate	η_{LCD}	-	4%
Peak luminance	L_{FOSmax}	nits	200
Average to peak ratio	$R_{a,p}$	-	0.9
Average luminance	L_{FOS}	nits	180

The required white color is usually stated in terms of the color temperature. This example is based on a required color temperature of 9000K and its chromaticity coordinates x=0.287 and y=0.298 (1931 diagram). Refer to Chapter 1, Figure 1.4, for more details.

In general, the color coordinates of the white point of the backlight are different from the color coordinates of the white point at the front of the screen. This difference is expressed in Δx_w and Δy_w and is determined by the light source spectrum and the LCD color filter characteristics. If these characteristics are not known, the difference can be assumed to be zero.

The color of the backlight can be tuned afterwards to obtain the desired FOS white point. In this example the LCD screen causes a color shift of 0,001 for both x and y. Therefore the xy color coordinates of the backlight need to be adjusted accordingly.

Each LCD has a transmission rate (ηLCD) that indicates the percentage of light from the backlight that actually passes the LCD. The exact value of ηLCD must be determined experimentally. However, the transmission rate for an LED backlight is typically 10% higher than the transmission rate for a CCFL backlight. This is because the red, green & blue LED spectra match the LCD red, green and blue filters. In this example for LED light the transmission rate ηLCD is assumed to be 4%, which means that out of every 100 nits emitted by the backlight only 4 nits are emitted from the front of the LCD.

Typically the highest luminance is required in the center of the display and it is allowed to have lower luminance at the edges. The quotient of average and peak luminance is expressed in $R_{a,p}$. A typical customer requirement for the peak luminance of a monitor is 200 nits.

$$L_{FOS} = L_{FOSpeak} \cdot R_{a,p} \qquad \text{Formula 2.1}$$

With the use of formula 2.1 the average required Front of Screen (FOS) luminance L_{FOS} is 180 nits with $R_{a,p} = 0.9$ (see table 2.1)

2.3 Backlight Requirement Calculations (Step 3)

The requirements of the backlight can be derived from the results of the previous section. Table 2.4 gives an overview of these backlight requirements for the 15" example. Important parameters for Luxeon DCC Light source are the backlight average Luminance L_{BL} and the color coordinates x_{wBL} and y_{wBL}. of the backlight.

Table 2.4 Calculated Backlight Requirements for 15" example

Backlight Parameters	Symbol	Unit	Value
Peak luminance	L_{Blmax}	cd/m2	5000
Average luminance	L_{BL}	cd/m2	4500
DBEF	f_{DBEF}		0.55
BEF	f_{BEF}		0.42
Required luminance	L_{Bldif}	cd/m2	2045
Backlight Chromaticity Coordinate (white)	x_{wBL}		0.288
	y_{wBL}		0.297
Intensity	I_{BL}	cd	142
Viewing angle (solid angle)	α	sr	2.60
Flux	$\Phi_{BL,T}$	lm	370
Backlight efficiency	η_{BL}	-	50%

The peak luminance FOS, in combination with the 4% transmission rate of the LCD can be used to determine the peak luminance of the backlight (L_{Blmax}).

$$L_{BL\ max} = \frac{L_{FOS\ max}}{\eta_{LCD}} \qquad \text{Formula 2.2}$$

With table 2.4 and Formula 2.2 the peak luminance L_{BLmax} is 5000 cd/m^2.

$$L_{BL} = L_{BL,max} \cdot R_{a\text{-}p} \qquad \textbf{Formula 2.3}$$

Now with formula 2.3 the average luminance can be calculated. The required average backlight luminance L_{BL} is 4500 cd/m^2.

Determining the Effect of Optical Films

In order to optimize the backlight efficiency, optical films such as Brightness Enhancement Films (BEF) and Depolarizing Brightness Enhancement Films (DBEF) may be placed between the backlight and the LCD. Formula 2.4 expresses the effect of the use of optical films on the required backlight luminance $L_{BL\&diffuser}$ (diffuser film only; without BEF).

$$L_{BL\&diffuser} = \frac{L_{BL}}{(1+f_{DBEF}) \cdot (1+f_{BEF})} \qquad \textbf{Formula 2.4}$$

With: DBEF gain factor f_{DBEF} of 0.55 (used in this example) and BEF gain factor f_{BEF} 0.42 (used as example) the required luminance $L_{BL\&diffuser}$ is 2045 cd/m^2, which means that the use of optical films reduces the required luminance from 4500 cd/m^2 to 2045 cd/m^2.
Note: The actual f-factors for the optical films used must be verified experimentally or with the vendor of the films.

Accounting for Color Shift From LCD Color Filters

The x and y coordinates of the backlight white point are determined from the required FOS coordinates, compensated for the color shift to the backlight that occurs in the LCD color filters.
The x and y coordinates are calculated by means of Formula 2.5:

$$x_{w,BL} = x_{w,FOS} + \Delta x_w$$
$$y_{w,BL} = y_{w,FOS} + \Delta y_w \qquad \textbf{Formula 2.5}$$

With the values for $x_{w,FOS}$, Δx_w, $y_{w,FOS}$ and Δy_w from Table 2.3, this results in:
$x_{w,BL} = 0.288$ and $y_{w,BL} = 0.297$ for the white color coordinates of the backlight.

Determining Luminous Flux Requirements

1.Intensity Calculations
The required backlight intensity I_{BL} is calculated from the required luminance and the display area.

$$I_{BL\&diffuser} = L_{BL\&diffuser} \cdot A \qquad \textbf{Formula 2.6}$$

This results in a required Intensity of 142cd in the 15" example (with A=0.07m^2 from Table 2.1).

2. Flux Calculations
In making the conversion from the Intensity (cd) to Flux (lumen), the viewing angle φ needs to be known. All the light emitted from the backlight is contained within this angle φ. Please note that in the calculations here, φ expresses the situation for a backlight with a diffuser only (without the optical enhancement films BEF and DBEF).
The backlight luminous flux can be calculated with Formula 2.7a) and 2.7b):

$$\Phi_{BL\&diffuser} = I_{BL\&diffuser} \cdot \Omega \qquad \textbf{Formula 2.7a)}$$

Where
$I_{BL\&diffuser}$ is the On-Axis Intensity (cd) from the diffuser sheet
Ω is the solid angle (sr)

$$\Omega = 2 \cdot \pi \cdot (1 - \cos \varphi_{1/2}) \qquad \textbf{Formula 2.7b)}$$

Where
$\varphi_{1/2}$ is the angle (°) from on-axis (0°) to where the intensity is 50% of the peak intensity.

With an Intensity $I_{BL\&diffuser}$ of 142 cd and a viewing angle of $\varphi1/2 = 54°$ or 2.6sr, the required flux that emits from the diffuser on the backlight, $\Phi_{BL\&diffuser}$ is 370 lumen for this example.

3. Calculating Optical Efficiency of Backlight Module
The optical efficiency of the backlight η_{BL} is defined as the luminous light output from the backlight plus diffuser $\Phi_{BL\&diffuser}$, divided by the light output of the light source into the backlight, $\Phi_{lightsource}$:

$$\eta_{BL} = \frac{\Phi_{BL\&diffuser}}{\Phi_{lightsource}} \qquad \textbf{Formula 2.8}$$

Thus the total flux requirements for the Luxeon DCC light source $\Phi_{lightsource}$ is 741 lumens.

The design specifications of the Lumileds Folded Mixing Light Guide (FMLG) concept play a crucial role in achieving a backlight optical efficiency of 50%. For more information on how to avoid light losses see Chapter 3, Optical Design, and Chapter 6, Mechanical Design.

2.4 Light Source Requirements (Step 4)

This step consists of calculating the required total flux $\Phi_{sum,T}$ for the light source and fractionating this flux into the required red, green and blue flux ($\Phi_{,R,T}$, $\Phi_{,G,T}$ and $\Phi_{,B,T}$ respectively) from the required backlight flux and color coordinates. Once the flux per color is known, the power consumption can be calculated. Table 2.5 gives an overview of the requirements on the light source resulting from the calculations.

The heat sink temperature T_{HS} is determined by the power dissipated in the Luxeon DCC light source and the cooling capacity of the thermal design. A realistic target heat sink temperature is 70°C. Chapter 4 provides more details on the different aspects of the thermal design, including a case study of a design example. In this chapter (2.4) the heat sink temperature is needed to translate the backlight requirements at temperature T_{HS} into light source optical specifications, which is given at an LED junction temperature T_j of 25°C.

Table 2.5 Requirements on the Luxeon DCC Light Source

Light Source Parameters	Symbol	Unit	Value
Target heat sink temperature	T_{HS}	°C	70
Required total flux from light source (at heat sink temp)	$\Phi_{sum,T}$	lm	741
Red flux needed at heat sink temp	$\Phi_{,R,T}$	lm	157
Green flux needed at heat sink temp	$\Phi_{,G,T}$	lm	553
Blue flux needed at heat sink temp	$\Phi_{,B,T}$	lm	31.0
Red flux needed at $T_j=25°C$	$\Phi_{,R,25}$	lm	296
Green flux needed at $T_j=25°C$	$\Phi_{,G,25}$	lm	658
Blue flux needed at $T_j=25°C$	$\Phi_{,B,25}$	lm	29.5
Total white flux at $T_j=25°C$	$\Phi_{,sum,25}$	lm	985
Red LED Power @ I=350mA	P_R	W	7.0
Green LED Power @ I=350mA	P_G	W	19.8
Blue LED Power @ I=350mA	P_B	W	5.0
Average white lm/W at 25°C	$\eta_{RGB,25}$	lm/W	31.0

Table 2.5 shows the requirements on the Luxeon DCC light source, derived from backlight requirements and the display requirements. The values are derived for the 15", 200 nits display example used in this application note.

The required total luminous flux from the light source $\Phi_{sum,T}$ at heat sink temperature can be calculated using Formula 2.8.

In this case, the required total flux ($\Phi_{lightsource}$) from the light source is 741lumens for a backlight with an optical efficiency of η_{BL} = 50% and a required flux $\Phi_{BL\&diffuser}$= 370lm from the backlight with a diffuser.

Determining Red, Green and Blue Flux at Heat Sink Temperature

Formula 1.11 has to be applied to calculate the amount of flux for each color. Using this formula, the required luminous flux for the red color is calculated by using Formula 2.9.

$$\Phi_{R,T} = \Phi_{sum,T} \cdot frac_R (x_w, y_w, x_R, y_Rx_G, y_Gx_B, y_B) \qquad \textbf{Formula 2.9}$$

This expression indicates the amount of red light as a function of the white color coordinates x_w and y_w and the color coordinates of the primaries red, green, and blue. In a similar way, the required flux for green $\Phi_{,G,T}$ and the required flux for blue $\Phi_{,B,T}$ can be calculated using the functions $frac_G$ and $frac_B$. See Annex B.

Determining Red, Green and Blue Flux at $T_{junction}$ = 25°C

The Luxeon DCC product data sheet specifies the luminous flux at a junction temperature of T_j = 25°C. The data sheet also provides information about the light output performance at elevated junction temperatures (see Figure 2.3). In a back-light application at steady state temperatures, the recommended board temperature is about 70°C and thus the junction temperature at approximately 85°C. In order to account for the change in light output at higher junction temperatures one needs to translate the light output requirements at elevated board- and junction temperatures to the light output at a junction temperature of 25°C.

The Red Flux **needed** at a junction temperature of 25°C is calculated using Formula 2.10:

$$\Phi_{R,25} = \Phi_{R,T} \cdot \theta_{R,T} \qquad \textbf{Formula 2.10}$$

where $\theta_{R,T}$ is the relative flux at $T_j=25°C$ when compared with flux at board temperature, see Figure 2.3
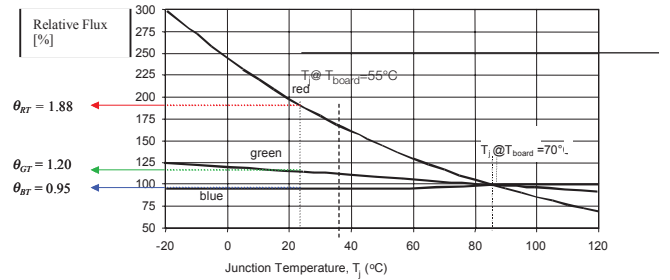

Figure 2.3 Relative Luminous Light Output vs. Temperature

Formula 2.10 can be applied in a similar way for Green and Blue. Applying these formulas and assuming a board temperature of 70°C results in the following required luminous flux values at 25°C junction temperature:
Red Flux: 296 lumen
Green Flux: 658 lumen
Blue Flux: 29.5 lumen
For heat sink temperatures other than 70°C, the flux correction factors θ have to be adjusted.

Example with a Board Temperature of 55°C:

If the board temperature is 55°C the relative light output value in Figure 2.3 has to be determined for each color at a junction temperature that is 15°C (70-55=15) lower than the intersection that corresponds to 70°C board temperature. For red, this results in a value of 120%. The red relative flux factor will thus become 1.88/1.20 = 1.57 for a heat sink temp of 55°C. For a more detailed explanation, see Annex G.

2.5 Selection of a Luxeon DCC Light Source (Step 5)

This step compares the results of Chapter 2.4 with the product specifications of the Luxeon DCC products in order to select the light source that delivers the required RGB performance.

Results of Step 4

Red flux needed at T_j=25°C	$\Phi_{,R,25}$	296	lm
Green flux needed at T_j=25°C	$\Phi_{,G,25}$	658	lm
Blue flux needed at T_j=25°C	$\Phi_{,B,25}$	29.5	lm

Table 2.6 Lumileds Product Specifications

LED Specifications	Unit	LXHL-MGAA	LXHL-MGBA	LXHL-MGCA	LXHL-MGDA	LXHL-MGEA
Red light output	lm	132	132	220	**440**	440
Green light output	lm	232	350	503	**696**	851
Blue light output	lm	14.8	37	52	**44.4**	59.2

The light output for the Red, Green and Blue LEDs needs to be the smallest value that is greater than or equal to the light output requirements shown in Table 2.6 above with the **results of step 4**. This means that the LXHL-MGDA is the appropriate Luxeon DCC light source that meets the requirements for the LCD-display specified in all previous steps.

The Luxeon DCC light sources will give optimum luminance and color uniformity if the screen length or width is equal to the length of the Luxeon DCC light source. A light source whose length exceeds the display size by more than 7.5mm is not advised.

Determining Power Requirements

The red flux values can now be used to approximate the power required for the red LEDs.

$$P_R = \frac{\Phi_{R,25}}{\left(\dfrac{\Phi_{R,0}}{V_{f,R} \cdot i_0}\right)}$$

Formula 2.11

Where

$\Phi_{,R,0}$ is the typical red light output (see Technical Data Sheet DS 48), 373lm for LXHL-MGDA.

$V_{f,R}$ is the forward voltage, both at 25°C Junction Temperature and 350mA (see Technical Data Sheet DS 48), $V_{f,R} = 2 \cdot 14.7V = 29.4V$ for LXHL-MGDA.

i_0 is 350mA.

Similarly the blue flux and the green flux can be used to calculate the power required for the green and blue LEDs. Applying formula 2.11 and assuming If=350mA/LED results in the following power values:

Red LED power	6.9W
Green LED power	20.3W
Blue LED power	4.8W

The required power plays an important role in the thermal design (see Chapter 4) and the specifications of the driver electronics (see Chapter 5).

Chapter 3: Optical Design

This chapter discusses the optical design of an LED based backlight in terms of the following topics:
· General design of the optical system
· Design of main components
· Performance
· Reference information

3.1 General Design of the Optical System

There are many possibilities for designing the optical system of an RGB LED based backlight. The information in this Application Note is based on Lumileds' FMLG (Folded Mixing Light Guide) concept. This concept attempts to balance efficiency, color uniformity, thickness and cost to deliver optimized results.

3.1.1 Main Components

Figure 3.1. shows the FMLG concept.
1. Luxeon DCC Light Source
2. Mixing Light Guide
3. Main Light Guide to be placed behind the LCD panel
4. A 90° Coupling Reflective Mirror
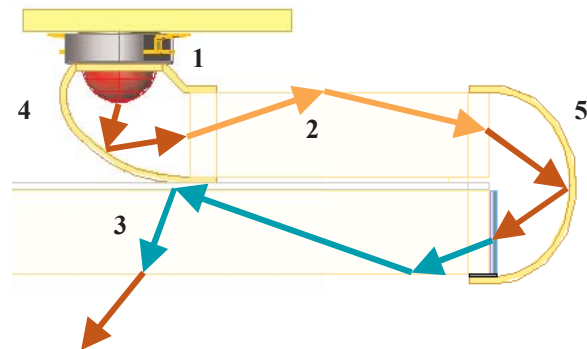5. A 180° Coupling Reflective Mirror

Figure 3.1 Components of an LED Based Backlight

The Luxeon DCC light source produces an RGB light that is coupled into the mixing light guide with a 90° mirror. This mixing light guide is used to mix the RGB colors into a uniform white light. The 180° mirror then directs this white light into the main light guide, where the light is uniformly distributed, and coupled out to the LCD.

3.1.2 Possible Configurations

The FMLG concept allows users to mount the Luxeon DCC light sources along:
· The top or bottom of the display
· The top and the bottom; requires two light sources
· The left or right side of the backlight
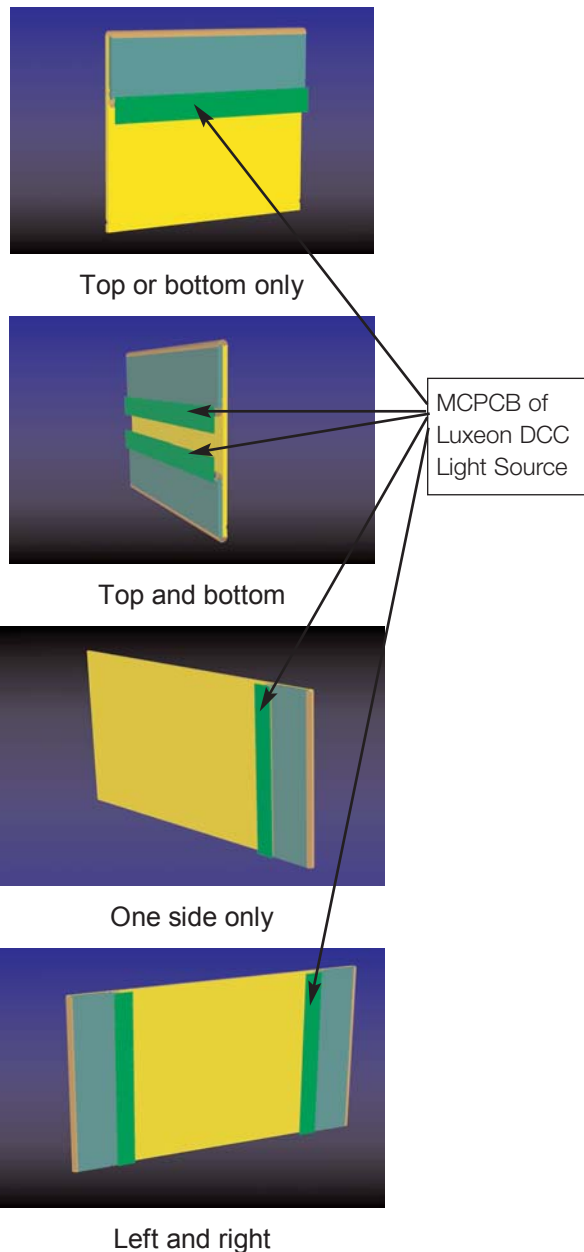· The left and the right side; requires two light sources

Top or bottom only

Top and bottom

MCPCB of
Luxeon DCC
Light Source

One side only

Left and right

**Figure 3.2   Possible Configurations for Mounting
the Luxeon DCC Light Source**

3.2 Design of Main Components

The design parameters of the main optical parts of the
backlight are:
· Mixing Light Guide
· Main Light Guide
· Coupling Mirrors

3.2.1 Mixing Light Guide

The light of the LEDs is coupled into the Mixing Light guide
with a 90° mirror. The function of the mixing light guide is to
mix the red, green and blue light and get uniform white light
by the time the light exits the other side of the mixing light
guide and enters the 180° mirror. In other words, the different
colors are captured inside the transparent light guide and due
to multiple reflections the colors mix to white light.

All light coupled into a light guide falls within the total internal
reflection (TIR) angle θ, (see also Chapter 3.4, Reference 2).
This angle is determined by the difference in refraction index
of the two media. For example, a medium (n=1.5) placed in
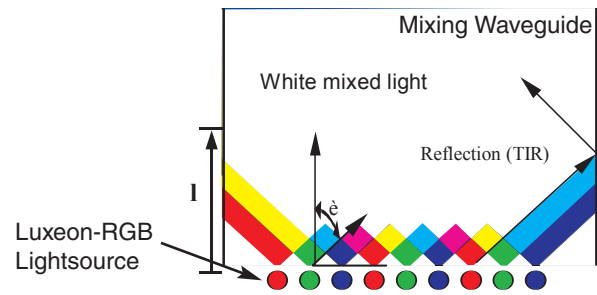air (n=1.0), will show a θ = 42°. See Figure 3.3.

Figure 3.3   TIR angle θ

The selection of a radiation pattern of the Luxeon emitter has
a direct impact on the distribution of the light inside the light
guide. Narrow viewing angle emitters require a longer mixing
length, but couple light more efficiently and vice versa. The
Lambertian radiation pattern balances both of these require-
ments well and is the reason that Lumileds has selected
Lambertian emitters for this product.

The following items need to be considered when designing
for the correct length of the mixing light guide:
· The pitch between individual emitters(set at 9mm in
  Luxeon DCC light sources)
· Spacing between same color emitters (optimized for
  different colors and different Luxeon DCC products)
· Index of Refraction of the light guide material(In the case
  of PMMA the index of refraction n is 1.5)
· Radiation pattern of the LEDs(Luxeon DCC use the
  Lambertian radiation pattern).

*Parameters of Mixing Light Guides for Different Luxeon
DCC Products*

Mixing Light Guide Length:
For this example, the maximum acceptable value for delta
u'v' is set to 0.010. See Chapter 1.1.1. In order to attain this
value, the minimum length of the mixing light guide must be:
· Light source LXHL-MGAA : > 75 mm
· Light source LXHL-MGBA : > 75 mm
· Light source LXHL-MGCA : > 95 mm
· Light source LXHL-MGDA : > 115 mm
· Light source LXHL-MGEA : > 115 mm

Table 3.1 Typical and Maximum Color Differences in △ u'v' Values for Different Lengths of the Mixing Light Guide

Dependence of Color Uniformity on Different Mixing Lengths for LXHL-MGAA and LXHL-MGBA		
Length l (mm)	△ u'v' Typical	△ u'v' Maximum
40	0,010	0,020
60	0,007	0,0014
75	0,005	0,010

Mixing Light Guide Width:
The width of the Luxeon DCC Light Source and the length of the mixing waveguide need to match. The width of the light guide should not exceed the length of the Luxeon DCC Light Source (+/- 5mm).

Mixing Light Guide Thickness:
Design considerations usually require a minimum thickness. Measurements of the relation between the thickness of the mixing light guide and the in-coupling efficiency, see Figure 3.4, have indicated that a thickness of 5mm gives a good coupling efficiency. The additional benefits of a thicker backlight are relatively low. A thickness of less than 4mm is not advised because an even thinner backlight results in significant in coupling light losses.
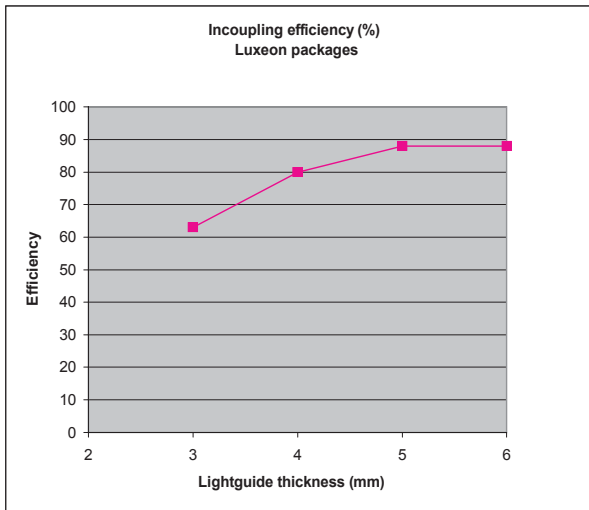

Incoupling efficiency (%) Luxeon packages

Figure 3.4 In-coupling Efficiency versus Thickness of the Mixing Light Guide

Surface
The surface of the mixing light guide should be polished in order to maximize the efficiency of total internal reflection (TIR). For the same reasons fingerprints and dust on the light guide must be avoided.

Anti-Reflection (AR) Coatings
AR-coatings on the in-coupling and out-coupling surface help to improve efficiency.

Material
A variety of PMMA materials can be used to produce the light guide. However, the choice should be based on the fact that the transmission of light through the PMMA should be as high as possible. In other words, the attenuation rate should be as low as possible. Lumileds regards 1% per inch as an acceptable rate. For more information on the attenuation rate of different PMMA materials, please refer to Annex C.

3.2.2 Main Light Guide
The main light guide in combination with an extraction pattern ensures a uniform out coupling of the light to the LCD. Extraction patterns on the back of the main light guide are realized either via screen printing or injection molded structures.

A reflective sheet behind the extraction pattern collects light that exits the light guide at the extraction pattern features and reflects it back into the light guide. Without such a reflective sheet this light would be lost.

Differences Between Main Light Guides for CCFL and Luxeon DCC
There are no major differences between a CCFL-based main light guide and an LED-based main light guide. The principles of a CCFL light guide can be applied to a light guide for Luxeon DCC.

Parameters of the Main Light Guide
The parameters and design advice of the Main Light Guide are shown below in Table 3.2.

Table 3.2 Parameters of the Main Light Guide

Parameter	Design Advice
Thickness	Lumileds advises an equal thickness of the main light guide and the mixing light guide (4mm-6mm).
Surface	Surface treatment should be similar to that of standard main light guides. Sides may be polished in order to improve the TIR efficiency.
Material	CCFL light guides required the addition of UV absorbers to prevent the LCD screen from being exposed to UV light. This does not apply for LED-based light sources.

Optical Feedback Sensor
The best way to maintain the white point of the backlight is to use an optical feedback sensor, for details see Chapter 5.3.2. The ideal location for such a sensor is in a position where color mixing is optimal. This is on the side opposite to where the light is coupled-in.
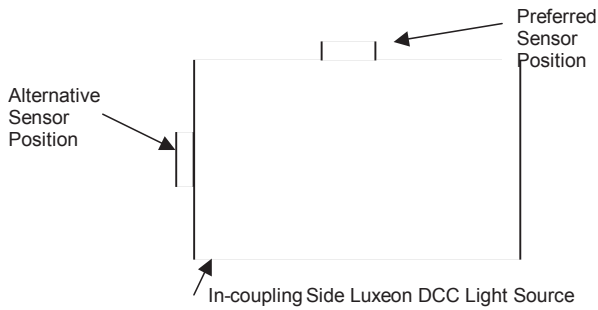
Figure 3.7 Placement options for XYZ Feedback Sensor

3.2.3 Coupling Mirrors

The 90° coupling mirror couples the light from the LED light source into the mixing light guide, and the 180° mirror couples the light from the mixing light guide into the main light guide. In both cases highly reflective mirrors are required.

Coupling Mirror Parameters

Material

The same material can be applied as is used in a typical CCFL configuration, i.e. MIRO® and ESR® foil (3M). ESR is available as foil or sheet metal with foils laminated on it. However, sheet metal is preferred when bending mirrors.

Shape

Both mirrors should have elliptical shapes. For the 90° mirror the first focus is positioned on the LED die and the second focus is in the center of the entrance of the mixing light guide. For more details, see Figures 3.7 and 3.8, which are based on a 6mm main light guide, also refer to Chapter 6.
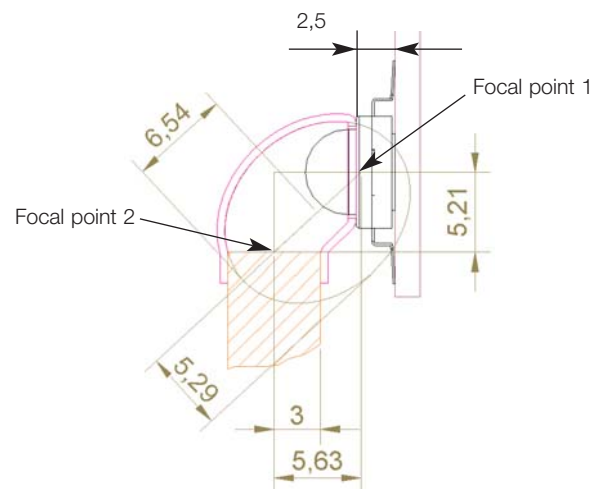

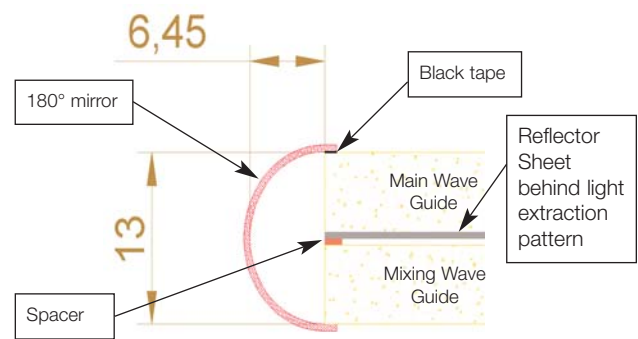Figure 3.8 Elliptical Shape of a 90° Mirror

Figure 3.9 Elliptical Shape of a 180° Mirror

Note: The elliptical shape of the mirrors is extremely important for the efficiency of the overall design. Please note that the design should prevent direct extraction of light out of the main light guide. Direct extraction will result in a high intensity band just above the mirror. This phenomenon can be avoided by applying a black tape on the front of the 180° mirror on the main light guide (for more details see Chapter 6.3, Black Tape).

3.3 Optical Performance

The optical performance of a LED based backlight can be measured by the following three criteria:

· Luminance
· Color Gamut
· Color Uniformity

3.3.1 Luminance

The performance in terms of luminance is shown in Figure 3.10. The optical power budget of the different components in the system is based on measurements made by Lumileds for this FMWG example.
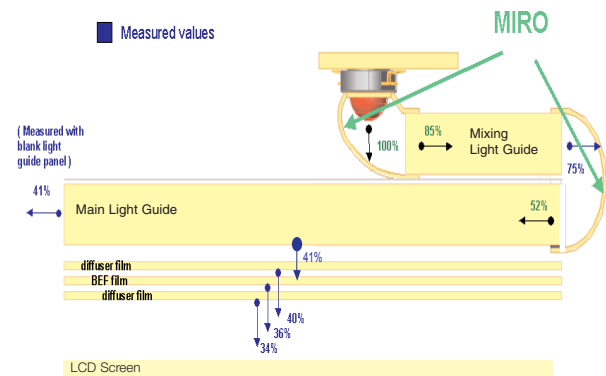

Figure 3.10 Optical Power Budget of Luxeon DCC FMLG Concept with MIRO Mirrors

41% toward bottom indicates BEF film on main light guide entrance with its effect.

The Total Backlight Efficiency (TBE) can be improved to 49% by applying 3M ESR foil on the 180° mirror or to 52% by applying this foil on both mirrors.

Measuring Luminance Uniformity

The measurements of luminance uniformity are usually based on a grid of points that are evenly distributed over the backlight. A typical grid size for evaluation during development is 15 x 11 points. During production of the display, the number of points can be reduced and often 17, 13, 9, and even 5-point grids are used. When a CCD camera is used there is no need to reduce the number of points in the production phase.

3.3.2 Color Gamut

Because the color image of an LCD screen is formed by the transmission of light through three different color filters, the spectral behavior between the light source and the filters is important.

The spectra of the LEDs are well adjusted to the different LCD color filters. However, small amounts of flux occur in the overlap regions.

In the green-blue overlap region, green light leaks through the blue filter. This has an impact on the resulting color gamut but can be reduced by shifting the blue filter into the shorter wavelength direction. See the dotted blue line in Figure 3.11.
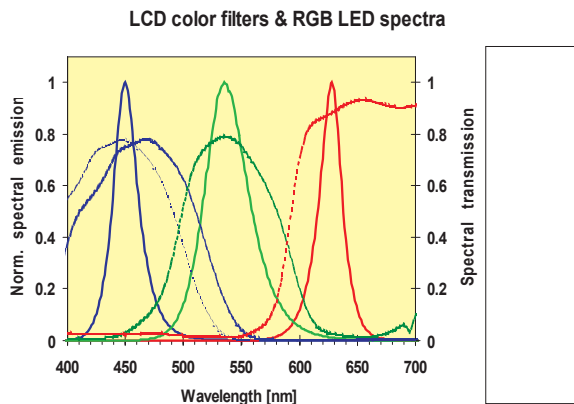
LCD color filters & RGB LED spectra

Figure 3.11 LCD Color Filters and RGB LED Spectra

Figure 3.11 Legend
1 = Blue LED Spectrum
2 = Green LED Spectrum
3 = Red LED spectrum
4 = Standard Blue LCD Filter
5 = Green LCD Filter
6 = Red LCD Filter
7 = Shifted Blue LCD Filter

In LCD displays the color gamut is determined by the typical spectrum of the LED light source and the color filters in the LCD. Since both the light source spectrum and the selection of a LCD with its filters can be selected, a wide variety of display gamuts can be realized.

In practice a trade-off must be made between color quality (color gamut) and the luminance. A large gamut area is obtained with narrow color filter spectra, whereas high lumi-nance is obtained with wide color filter spectra that collect as much light as possible.

The determination of the color gamut size starts with the exact color points of the Luxeon DCC light source in xy-space. Then the total area is calculated from this triangle and this is then compared to the area of the NTSC triangle. A value of well over 100% NTSC is possible.

3.3.3 Color Uniformity

Chapter 1 describes the use of Δu'v' as parameter for expressing color uniformity, i.e. the deviation of any point with respect to a chosen reference value. Although the FMLG concept can produce light with a color uniformity of 0,008 (see Chapter 3.2.1), it is more realistic to expect a color uniformity of 0,01 due to production tolerances. The color uniformity is measured in a similar way as the brightness uniformity, using a grid (see Chapter 1.1.1 for measurement method).

3.4 Reference Information

1. High-efficiency Slim LED Backlight System with Mixing Light Guide Yourii Martynov, Huub Konijn, Nicola Pfeffer, Simon Kuppens and Wim Timmers SID 03 DIGEST p.1259.
2. Optics, by Hecht, publ. Addison-Wesley, ISBN 0-201-11611-1 page 104.
3. The IESNA Lighting Handbook, ISBN 0-87995-150-8.
4. High Brightness Light Emitting Diodes by Stringfellow and Craford, ISBN 0-12-752156-9.
5. Introduction to Solid State Lighting, by Zukauskas, Shur and Gaska publ. John Wiley & Sons, ISBN 0-471-21574-0.

Chapter 4: Thermal Design

The performance of backlight applications with Luxeon DCC products relies on a proper thermal design. The benefits of a good thermal design are the following:
- Higher flux from the LEDs, resulting in higher screen brightness
- Lower power consumption.
- Better lumen maintenance over the lifetime of the product.
- Virtual zero failure rate when Luxeon DCC operates within its recommended temperature range.

This chapter discusses the following aspects of heat management:
1. Generation of a Thermal Model.
2. Design rules for a flat plate heat sink.
3. System thermal design and integration in a monitor housing.
4. Case study of the thermal design of a FMLG (Folded Mixing Light Guide) prototype.
5. Reference information.

4.1 Generation of a Thermal Model

The purpose of this chapter is to generate a basic thermal model for a Luxeon DCC based backlight application, and then to apply this model to predict the junction temperature of Luxeon DCC LEDs. The junction refers to the p-n junction within the semiconductor die, where the energy is partially converted to photons and partially converted to heat. A proper thermal design controls the junction temperature such that it stays below the data sheet maximum of 120°C (see Data Table "Absolute Maximum Ratings").

Thermal Model for a Luxeon on a Flat Plate Heat Sink

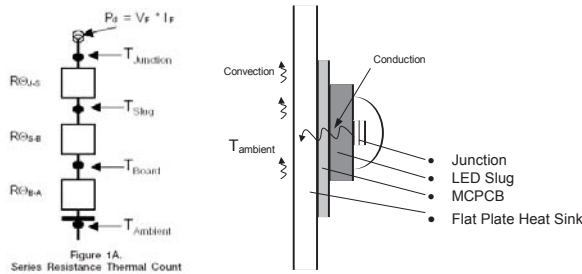Figure 4.1 illustrates the thermal model of a Luxeon LED mounted on a flat plate heat sink.

Figure 4.1 Thermal Model of a Luxeon LED on a flat plate heat sink

In this application note we assume that all dissipated power, Pd, is converted to heat. This is a conservative assumption. In reality about 10% to 15% of the dissipated power is converted to light. Another assumption is that all the heat that is generated at the pn-junction is conducted to the flat plate heat sink and then transferred through convection to the ambient air. In reality there is also a small amount of energy that radiates away from the heat sink. However this amount is negligible . The heat has to overcome thermal resistances when it travels from the pn-junction to the slug, the MCPCB, the heat sink and then to the ambient. This thermal resistance causes for a temperature gradient from the pn-junction (hottest point) to the ambient (coolest point). The thermal resistance, the temperature gradient and the dissipated power are proportional to each other and can be described with Formula 4.1.

$$R_{th\_junction-ambient} = \frac{\left(T_{junction} - T_{ambient}\right)}{P_d}$$

and **Formula 4.1**

$$R_{th\_board-ambient} = \frac{\left(T_{board} - T_{ambient}\right)}{P_d}$$

Reference: AB05, Formula 1

Thermal Model for a Luxeon DCC light source on a Flat Plate Heat Sink in a backlight module

The principles of thermal management with a flat plate heat sink can be applied towards the thermal design of a Luxeon DCC light source in a Folded Mixing Light Guide assembly. Figure 4.2 shows that in such a thermal model the heat has

two paths to conduct from the MCPCB. One, via the back of the heat sink to the ambient and the second via the front of the heat sink, through both light guides, to the front of the screen, and then to the ambient. The heat is brought to the outer surfaces of the assembly via conduction, and then the heat is brought to ambient temperature via convection of air.
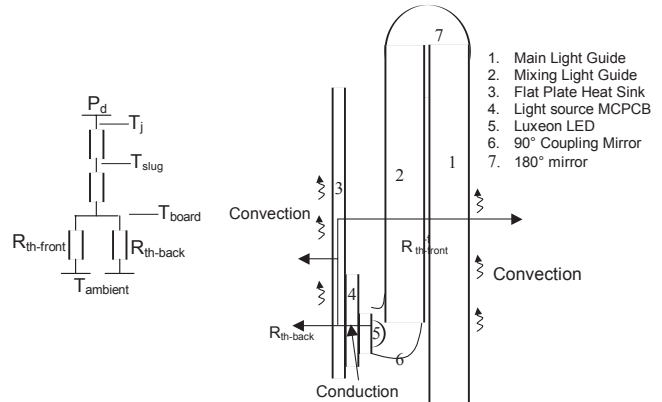

Figure 4.2 Thermal Model of Luxeon DCC in a FMLG Concept with Parallel Thermal Resistances Though Front and Back

General Thermal Design Considerations for a Luxeon DCC Applications

A thermal design has to manage the following temperature related requirements:

1. Maintain the recommended MCPCB temperature of a Luxeon DCC light source at approximately 70°C (see data sheet).
2. Enable reliable operation at worst-case maximum ambient temperatures.
3. Effectively conduct and convect heat that is generated at the junction through power consumption away from the Luxeon DCC light source (management of total thermal resistance)

Note: In this Application Note the maximum ambient temperature of the backlight is defined as the temperature near the backlight heat sink. Thus when the backlight heat sink is enclosed in a housing, then the maximum ambient temperature is the temperature near the heat sink inside the housing. From a given ambient temperature or board temperature and a given total power dissipation one can determine the required thermal resistance. Once the required thermal resistance has been determined then several heat sink options with the same thermal resistance should be evaluated. Table 4.1 shows an overview of the benefits and drawbacks of different heat sink options.

Table 4.1 Heat Sink Strategies, Benefits and Drawbacks

Solution Type	Benefits	Drawbacks

Flat plate heat sink	+ Thinness
	+ Costs
	+ Weight
		- Limited cooling
		  capacity with
		  thin plates

Finned heat sink	+ Good cooling capacity + Smaller foot print	- Thickness - Costs

Fan solution in combination with flat plate heat sink	+ Airflow increases
	  heat transfer coefficient
	  from plate-to-air
	+ Compact design
	  possible
		- Noise
		- Thickness
		- Additional power
		  consumption
		- Lifetime of fan

Note: The flat plate design assumes that the available size of the heat sink is equal to or smaller than the size of the display.

4.2 General Rules for Thermal Designs with a Flat Plate Heat Sink

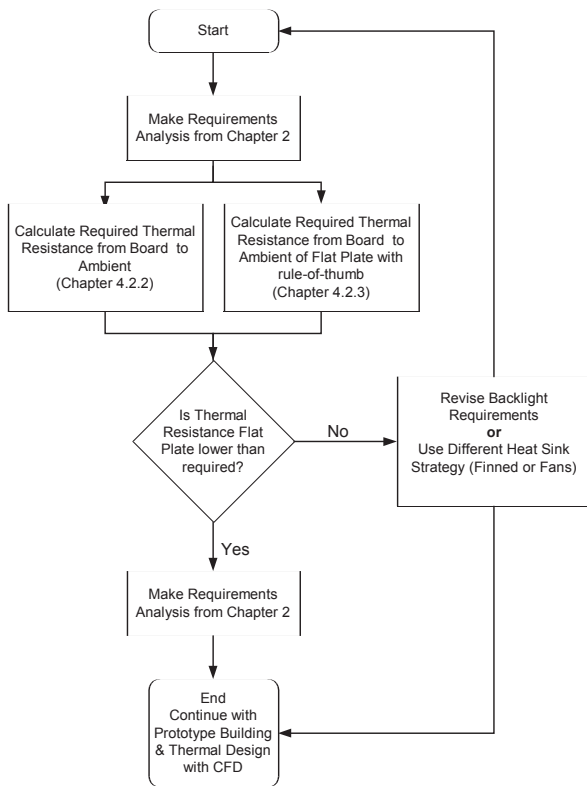### 4.2.1 Recommended Thermal Design Process for Flat Plate Heat Sink Design

Figure 4.3 Thermal Design Process for Flat Plate

4.2.2 Calculation of the Required Thermal Resistance Board-to-Ambient

In general there are two different situations that are important to evaluate:

1. **Worst case operating conditions:** Consider highest ambient temperature and maximum power dissipation.

In such a case the maximum board temperature should not exceed 100°C.

2. **Typical Operating Conditions:** Consider typical ambient temperatures and typical power dissipation. At these typical conditions the board temperatures should be approximately 70°C.

First, determine the worst case operating conditions and use that to determine the minimum board to ambient thermal resistance. Use Formula 4.1 for these calculations.

$$R_{th\_board-ambient} = \frac{(T_{board} - T_{ambient})}{Pd} \qquad \textbf{Formula 4.1}$$

Example
Calculation of the required Board-to-Ambient Thermal Resistance for Typical and Worst-Case Situations

System Configuration:
· Display size: 15"
· Type of Luxeon DCC Light source: 1 x LXHL-MGDA
· Typical ambient temperature inside the housing: 35°C
· Worst case maximum ambient temperature inside the housing: 60°C

Table 4.2 Calculation of Required Thermal Resistance for Typical and Worst Case Conditions

Description	Symbol	Typical Operating Conditions	Worst Case Situation	Unit
Dissipated LED Power	P_d	33.6	40.8	W
MCPCB Temperature	T_{board}	70	100	°C
Junction Temperature	T_j	85	115	°C
Ambient Temperature	T_{amb}	35	60	°C
Calculated board-to-ambient Thermal Resistance (Formula 4.1)	R_{th}	1.0	1.0	K/W

Note: This calculation assumes a worst-case 1.2W maximum power dissipation of every single Luxeon LED. LXHL MGDA contains 34 LEDs and therefore the maximum power dissipation of an LXHL-MGDA light source is 40.8W. In comparison, the typical power consumption that is needed to maintain a 9000K white point is only about 33.6W. This is because the current of certain color LEDs is tuned down such that the color mix results in a stable CCT of 9000K on the black body locus.

Part Number	Typical Power (W) @ 9000K	Maximum Power (W) all LEDs @ 350mA
LXHL-MGAA	10.3	13.2
LXHL-MGBA	14.9	20.4
LXHL-MGCA	24.2	30.0
LXHL-MGDA	33.6	40.8
LXHL-MGEA	41.3	48.0

4.2.3 Estimation of Thermal Resistance with Flat Plate Design

Thermal Model of a Generic Backlight

The mechanical design of a typical backlight consists of several layers of different materials and air gaps. Every layer has its own specific thermal resistance. Because the construction of most backlights is made in a similar way and with similar materials, a generic thermal model works for most of the designs. The generic model assumes that there are the following two dominating thermal paths:

1. Conduction from the MCPCB to the back plate at the back of the display and convection from the back plate to the ambient.
2. Conduction from the MCPCB to the front of the display via the main light guide, the optical enhancement films, and the LCD and convection from the LCD to the ambient.

Rules-of-Thumb Development

For backlights that are arranged similar to a structure as it is described in annex D, the total heat transfer can be estimated from the thermal resistance and the heat transfer coefficient of the outer surfaces.

Thermal measurements on prototypes and theoretical calculations resulted in an average heat transfer coefficient of 15 W/m^2K for such generic backlights. This heat transfer coefficient should be used to make a first order estimation of the expected board temperature. If necessary the thermal design should be refined with Computational Fluid Dynamics (CFD).

Next a designer needs to distinguish flat plate heat sinks with different heights. Flat plates with a height of less than 200mm are relatively more efficient. This is because with convection the air warms up as it travels on the heat sink surface from the bottom to the top and thus makes the heat sink less efficient a the top. The rule of thumb has to be adjusted accordingly.

Use Formula 4.6a for heat sinks **that are higher** than

$$200mm: R_{th\_MCPCB-ambient} = \frac{1}{h*A}$$

Use Formula 4.6b for heat sinks that are shallower than 200mm:

$$R_{th\_MCPCB-ambient} = \frac{1}{\left[(26.15-0.065*H)*A\right]}$$

Where:

h	= heat transfer coefficient [15 W/m^2K]
H	= heat sink height [mm]
A	= Flat plate area or display area [m^2]
T_{amb}	= temperature near the heat sink [°C]
Surface of heat sink	= black anodized aluminum

Estimation of the Board Temperature with the Rule of Thumb Design Tools

Example:

System Specification:

Display Size:	15"
Light Source:	LXHL-MGDA (Luxeon DCC)
Power Dissipation Luxeon DCC Light Source:	P_{typ} = 33.6W (from Table 4.2)
Heat Sink Area:	A = 0.228m x 0.305m = 0.07m^2
Ambient Temperature:	$T_{amb-inside\ housing}$= 35°C

Estimated Thermal Resistance MCPCB to ambient with the use of the Rule of Thumb:

The height of the heat sink is more than 200mm and therefore formula 4.6a applies:

$$R_{th\_MCPCB-ambient} = \frac{1}{h*A} = \frac{1}{15W/m^2K*0.07m^2} = 0.96K/W$$

$$T_{board} = T_{ambient} + R_{th\_MCPCB-ambient} * P_{d\_typ}$$
$$= 35°C + 0.96K/W * 33.6W = 67°C$$

Heat Sink Design and Strategies

When the 'required thermal resistance' (from chapter 4.2.2.) is compared with the 'estimated thermal resistance' based on flat plate cooling, there are three possible results:

1. $R_{th,\ flat\ plate} << R_{th\_MCPCB-ambient,\ required}$: Continue thermal design
2. $R_{th,\ flat\ plate} >> R_{th\_MCPCB-ambient,\ required}$: A flat plate heat sink is not sufficient, design a different heat sink
3. $R_{th,\ flat\ plate} \sim R_{th\_MCPCB-ambient,\ required}$: Refine Thermal Design with the use of CFD.

In the example above the 'estimated thermal resistance' is 0.96 K/W and the required thermal resistance is 1.0 K/W. This means that the thermal design needs to be analyzed with the use of a prototype and/or CFD. Dependent on the results the heat sink strategy may need to be changed.

4.2.4 Determination of the Thickness of a Flat Plate Heat Sink

The effectiveness of a heat sink depends very much on the spread of the heat over its total surface. In case of a flat plate heat sink the conductivity of the material and its thickness are important parameters. Aluminum is the recommended material for flat plate heat sink designs, because of its good

cost/thermal performance ratio. However, it is important to determine the required thickness so that the heat is spread throughout the entire flat plate heat sink, and balance this with the additional weight and cost of a thicker flat plate heat sink.

The following two parameters need to be considered when determining the thickness of a flat plate heat sink:
1. The largest distance from the heat source (or light source) to the edge of the heat sink.
2. The acceptable temperature gradient from where the light source is to the edge of the heat sink. The smaller this temperature gradient, the better the heat is distributed on the flat plate heat sink, the more efficient the flat plate heat sink is.

First, the largest distance from the light source to an edge of the heat sink may be obtained from the construction of the backlight (side or top/bottom placement) and the required screen size.
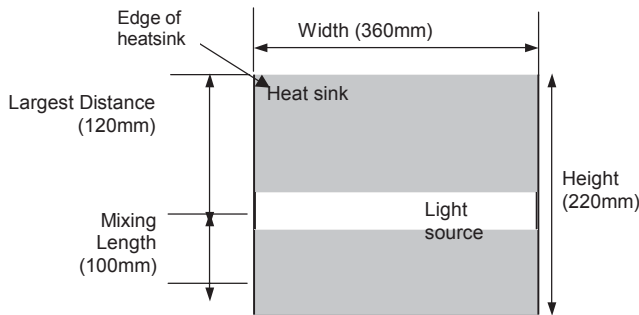

Figure 4.4 Overview of an 18" Flat Plate Heat Sink Design (Light Source at Bottom)

Secondly, Figure 4.5 provides a graph that defines the required thickness of a flat plate heat sink. This graph assumes the following:
1. The light source acts as a uniform heat source.
2. The temperature at the furthest edge of the flat plate heat sink is minimum 75% of the temperature where the light source is.
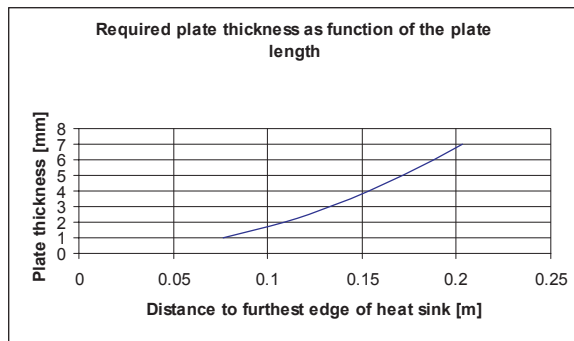

Figure 4.5 Thickness Heat Sink vs. Largest Distance Light Source from Heat Sink Edge

Example: Determination of Thickness of a Flat Plate Heat Sink:
When using an 18" backlight with the FMLG concept and the light source is located 0.12m away from the furthest edge of a flat plate heat sink, then the required thickness of a flat plate heat sink is 2.5mm.

Trade-off Between Thermal Resistance and Thickness
In principle, a thicker flat plate heat sink reduces the thermal resistance of the system, but it will also add cost and weight to the system. Figure 4.6 shows that there is a trade-off between thickness and reduction of thermal resistance.
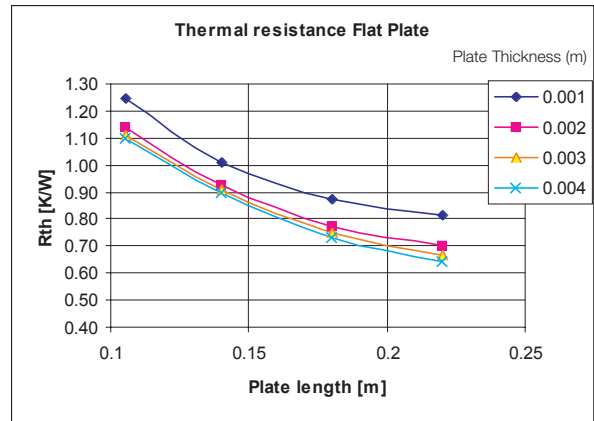

Figure 4.6 Trade-off Between Thermal Resistance and Flat Plate Thickness for Different Lengths (18'' Backlight with a Flat Plate of 360mm Width)

Calculating again the thermal resistance of the 18" flat plate heat sink with its dimensions of 360mm x 220mm and with the heat source located as shown in Figure 4.4, a thickness of 2mm gives a good trade-off between lowering the thermal resistance and reducing the thickness of the flat plate heat sink.

Table 4.4 provides an overview of thermal resistances board to ambient that have been calculated with the use of the Rule of Thumb for different screen sizes and aspect ratios.

Table 4.4   Typical Thermal Resistance (K/W) of a Flat Plate Based Cooling Solution

| | Thermal Resistance [K/W] | |
Screen Size (inch)	Aspect Ratio: 4:3	Aspect Ratio: 16:9
7	4.4	14.9
15	1.0	-
18	0.66	0.75

Note: For more choices please see Annex F.

4.3 Overview Selection Table for Maximum Power and Heat Sink Thickness

The Table 4.5 can be used to determine the maximum power, based on light source and screen size. Table 4.6 describes the required plate thickness.

Table 4.5 Estimated Maximum Power Dissipation for a Flat Plate Heat Sink at T_{MCPCB}=70°C and $T_{ambient}$=35°C

Luxeon DCC Part Number	Top or Bottom 4:3	Top or Bottom 16:9	Left or Right 4:3	Left or Right 16:9
LXHL-MGAA	4 W	3 W	8 W	9 W
LXHL-MGBA	10 W	7 W	16 W	21 W
LXHL-MGCA	19 W	15 W	35 W	47 W
LXHL-MGDA	35 W	29 W	70 W	88 W
LXHL-MGEA	53 W	39 W	88 W	117 W

Table 4.6 Estimated Plate Thickness for a Uniform Temperature Gradient of a Black Anodized Aluminium Flat Plate(1060A)

Luxeon DCC Part Number	Top or Bottom 4:3	Top or Bottom 16:9	Left or Right 4:3	Left or Right 16:9
LXHL-MGAA	1 mm	1 mm	1 mm	1 mm
LXHL-MGBA	1 mm	1 mm	1 mm	2 mm
LXHL-MGCA	1 mm	1 mm	1 mm*	1 mm*
LXHL-MGDA	2 mm	1 mm	1.5mm*	3 mm*
LXHL-MGEA	3 mm	2 mm	2 mm*	4 mm*

* = based on double sided solution

4.4 Current Derating

When following the design rules of this Application Note the junction temperature should always be below its maximum value. In situations where the ambient temperature exceeds the maximum allowable ambient temperature that was chosen during the design, the average LED current may need to be reduced to prevent the junction temperature from exceeding its maximum.

The current derating curve (Data Sheet 46 Figure10, or Figure 4.6) should be used to set the average current per LED, depending on ambient temperature and the thermal resistance from board to ambient.
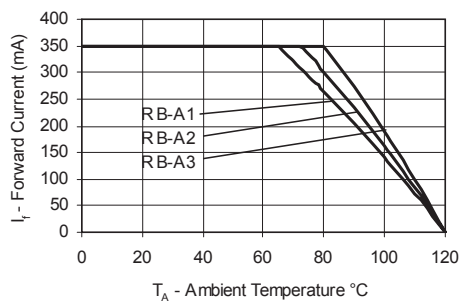

Figure 4.7 Current Derating Curves and Thermal Resistances Board to Ambient

Part Number	R_{B-A1} Flat Plate Heat Sink With Fan Cooling (°C/W)	R_{B-A2} Flat Plate Heat Sink (°C/W)	R_{B-A3} Finned Heat Sink (°C/W)
LXHL-MGAA	3.5	2.8	2.1
LXHL-MGBA	2.3	1.9	1.4
LXHL-MGCA	1.5	1.3	1.0
LXHL-MGDA	1.1	0.9	0.7
LXHL-MGEA	1.0	0.8	0.6

Note: RB-A1 represents a combination of flat plate and fan cooling, R_{B-A2} represents flat plate cooling, R_{B-A3} represents fined heat sink cooling.

For example: A 15" backlight with an LXHL-MGDA light source in a system with $R_{B-A} = R_{B-A1} = 1.1$°C/W, can be driven at its maximum current up to an ambient temperature of 65°C. As soon as the ambient temperature exceeds 65°C the electrical power needs to be reduced according to the derating curve in figure 4.7.

4.5 Integration into a Monitor Housing

Drive electronics increase the thermal load inside the housing of a monitor and this changes the thermal behavior of the system. Generally there are two effects that are being caused by the drive electronics in a monitor housing:

· The **ambient** temperature of the backlight changes
  · due to heat generation from the Luxeon backlight, and
  · due to heat generation from other electronics, such as LCD drivers and power supplies.
· The **efficiency** of the heat sink changes
  · Due to higher ambient temperatures
  · Due to a different heat transfer coefficient caused by blockage or changing thermal radiation

These effects should be minimized by keeping the following design rules in mind:

· The use of high efficiency electronics will reduce the heat generation. In principle, there is always a trade-off between the efficiency of the electronics and the required heat sink design
· Allow as much free airflow as possible by
  · Designing holes at the bottom and at the top of the monitor housing
  · Re-rout objects that prevent free airflow

4.6 Case Study of an 15" FMLG Prototype

4.6.1 Case Study Outline

This case study discusses the design process of a heat sink for a 15" monitor with a 4:3 aspect ratio. To achieve the required luminance the design is based on the following:

1. Design is an FMLG bottom arrangement, see Chapter 3, Figure 3.2, bottom.
2. One Luxeon for backlighting light source module type D (34 LEDs)

The nominal board temperature is 70°C (see Data Sheet DS48) at an ambient temperature of 35°C. The backlight is not integrated in a monitor housing.

4.6.2 Assignment
Compare theoretical and experimental results of free and forced air-cooling.

4.6.3 Method
1. Sketch a draft design and apply the rule-of-thumb.
2. Generate a CAD drawing and conduct a computer based thermal analysis (CFD).
3. Build a prototype and perform thermal measurements.
4. Validate the thermal model and, if required, make a redesign.

Figure 4.8 shows the process that was used for this 15" monitor case study
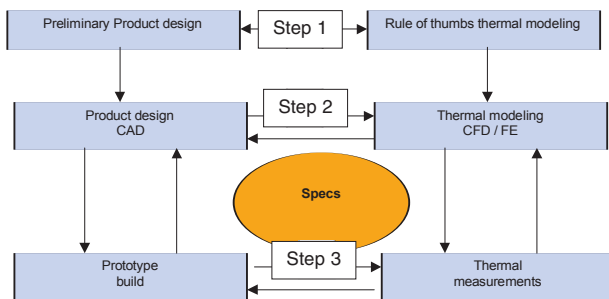

Figure 4.8 Thermal Case Study Design Process

4.6.4 Design Based on Sketch and Rule of Thumb
At the start a draft sketch needs to be generated. Figure 4.9. shows the sketch that was used for the 15" monitor case study. The design uses the front and the back for cooling.
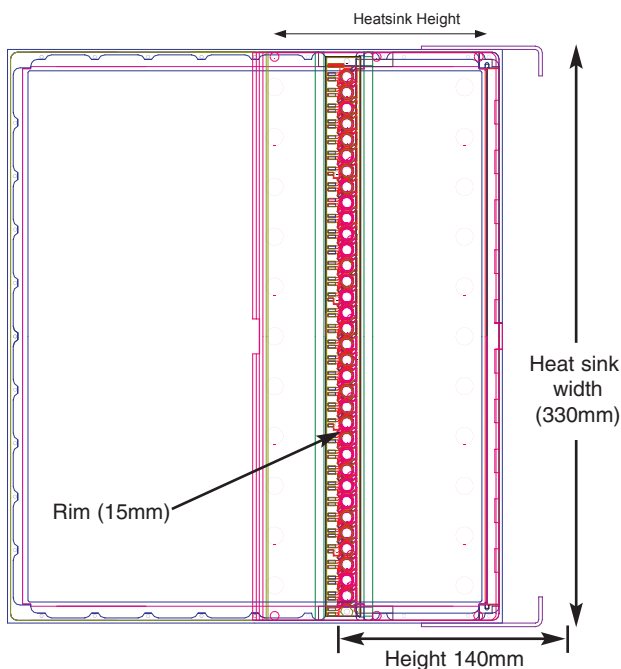

Figure 4.9 Design Sketch

From this sketch the heat sink area can be calculated. The heat sink has a height of 140mm, a width of 330mm and a rim of 15mm. Therefore, the heat sink area is:
$A = h \times w = (0.14m + 0.015m) \times 0.330m = 0.051m^2$.
With the rule-of-thumb for a black anodized aluminum vertical plate a first estimation of the thermal resistance can be made. Since the height of the heat sink is smaller than 200mm, formula 4.6b is used.

$$R_{th} = \frac{1}{\left[(26.15 - 0.065 * H) * A\right]}$$ **Formula 4.6b**

This results in an estimated thermal resistance:

$$R_{th\_MCPCB-ambient} = \frac{1}{\left[(26.15 - 0.065 * 155mm) * A\right]}$$ **Formula 4.6**

$$= \frac{1}{16.07 * 0.051m^2} = 1.22K/W$$

The resulting thermal resistance can now be used to calculate the estimated temperature increase of the MCPCB.
$\Delta T_{\_MCPCB-ambient} = P \times R_{th}, = 40.8W \times 1.22°C/W = 49.7°C$
with P_{max} of 34 LEDs = 40.8W and $R_{th\_MCPCB-ambient} = 1.22K/W$.

This means that:
$T_{MCPCB} = T_{amb} + \Delta T_{\_MCPCB-ambient} = 25°C + 49.7°C = 74.7 °C$.

The result shows that the temperature of the light source module is close to the recommended board temperature. Therefore per 4.2.3, CFD simulations and a prototype build is necessary to verify the values.

4.6.5 Prototype Builds and Thermal Measurements
The sketch in Figure 4.9 is the basis for prototype builds and numerical simulations. The required thickness of the flat plate heat sink was obtained from Figure 4.5. In this example the largest distance between the light source and the edge of the heat sink is 100mm and therefore the thickness of a flat plate heat sink should at least be 1.5mm. For this case study it was decided to use a 2mm thick plate.

Measurements of the power dissipation showed that it is 30.9 W when the white point is adjusted for 9000K. The above-described system has also been modeled using a commercially available CFD software package. Table 4.7 provides an overview of the results obtained.

Table 4.7 Temperature Differences Between Heat Sink and Ambient Temperature from Rule-of-Thumb, CFD Simulations, and Measurements

$\Delta T_{MCPCB-ambient}$			
Rule of Thumb P_{in} = 40.8 W (form 4.6)	Rule of Thumb P_{in} = 30.9 W (form 4.6)	Numerical Calculations P_{in} = 30.9 W	Temperature Measurements P_{in} = 30.9 W
49.7°C	37.7°C	31.4°C	32°C

Effects of Material Properties and Surface Treatments.

In order to get a good thermal performance of a flat plate heat sink, the selection of materials with good thermal properties and appropriate surface treatments are important. Using the same system setup as in Chapter 4.6.5 the temperature differences are measured for a blank aluminum plate heat sink and a galvanized steel plate. See Table 4.8.

Table 4.8   Effects of Material Choice and Surface Treatment

$\Delta T_{MCPCB\text{-}ambient}$		
Aluminum Untreated P_{in} = 30.9 W	Steel P_{in} = 30.9 W	Black Anodized Aluminum P_{in} = 30.9 W
46°C	49°C	32

4.6.6 Conclusions and Recommendations

This case study results in the following conclusions and recommendations.

1. At the required white point, the temperature of the light source module stays well below the recommended temperature of 70°C.
2. The rule of thumb, simulations and measurements results are in close proximity
3. When the unit is enclosed in a housing, the temperature inside the housing has to be used as ambient temperature.

4.7 Reference Information

1. http://www.r-theta.com/products/extrusion/part1.pdf.
2. AB05 Thermal Design Using Luxeon Power Light Sources, see Chapter 1.4, Reference 1.
3. http://www.coolingzone.com for general information on thermal management

Chapter 5: Electrical Design

This chapter describes the electrical aspects of the Luxeon DCC FMLG concept in terms of the following two main topics:

1. Electronics that drive the Luxeon DCC light source.
2. Methods that control the driver of the Luxeon DCC light source.

The benefits of a properly designed LED control circuits include:

· Fine-tuning capabilities of the desired color point (i.e. white point) and the desired luminance by the user.
· Reduction of motion artifacts due to fast blinking capabilities of an LED backlight.
· Color sequential blinking backlight in combination with a black / white LCD panel.
· Avoidance of variations in on-screen performance (color point- and luminance) due to LED variations over time and temperature.
· Reduced power consumption.

5.1 System Overview

Figure 5.1 shows a functional model of a Luxeon DCC driver.
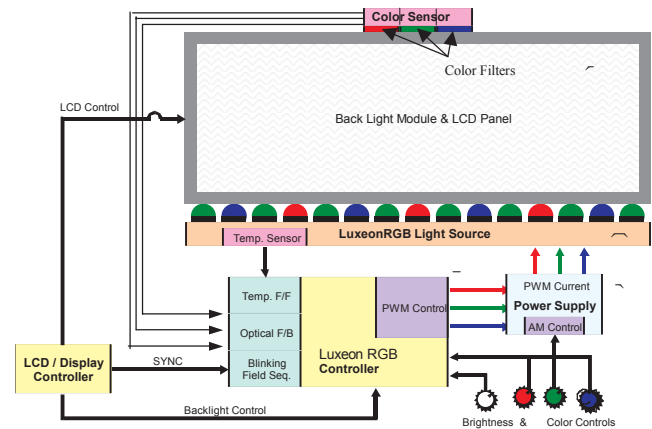

Figure 5.1 Functional Model of a Luxeon DCC Driver

This model has four main blocks:

1. Luxeon DCC Light Source.
2. Backlight Module and LCD Panel (see Chapter 3, Optical Design for information on how the backlight module works)
3. Switch Mode Power Supply (SMPS) - The power supply provides the LEDs with power. The selection of a recommended type of Switch Mode Power Supply is discussed in Section 5.2 of this Chapter.
4. Pulse Width Modulation (PWM) Controller - The purpose of a controller is to set the brightness's of the individual red, green and blue channels via sensor feedback and/or user settings. The selection of a recommended type of PWM controller is discussed in Section 5.3 of this Chapter.

5.2 Electronics for Driving a Luxeon DCC Light Source

5.2.1 Methods for Driving a LED

In general LEDs have a non-linear I-V behavior and thus current limitation is required to prevent the power dissipation to exceed a maximum limit. Thus the ideal source for LED technologies is a constant current source. A driver consists of two parts:

1. Primary side: Converts the input or supply voltage to an appropriate voltage or current for the LED light source. In other words, it provides the secondary side (LED side) with the necessary energy. Possible concepts are:
   · Linear Power Supply
   · Switch Mode Power Supply (SMPS)
2. Secondary side: Controls the current through the LEDs. Possible configurations are:
   · Constant Voltage Source with a series resistor
   · Constant Current Source
   · Pulse Width Modulation (PWM) or Amplitude Modulation (AM) to maintain a constant average current; See Chapter 5.2.3

Primary Side Configurations

There are two commonly used architectures on the primary side:

· Linear Current Drive
· Switch Mode Power Supply (SMPS)

SMPS when compared to linear current drives have higher efficiencies and thus generate less heat and consume less power. SMPS use high switching frequencies to charge energy storing devices such as inductors and capacitors and therefore SMPS circuits require special attention to the reduction of Electromagnetic Radiation (EMI) caused by the high frequency switching.

Secondary Side Configurations

There are two commonly used methods for applying current to the LEDs:

· Constant Voltage Source with series resistor
· Constant Current Source

With a constant current source the design is independent from the use of different forward voltage bins and forward voltage variations over temperature.

With a constant voltage source these effects have to be taken into account to avoid current variations with LEDs from different forward voltage bins. To set the same current for LEDs from different LED voltage bins one needs to design with matched resistor values.

Generic Specifications of the Power Supply

To meet the optical requirements of the FMLG backlight concept, the power supply must meet the following specifications:

1. Three-channel driver to allow optimal individual control over Red, Green and Blue LED currents.
2. Current output per channel:
   · Constant current: 350mA for blue and green (InGaN); 385mA for red (AlInGaP)
   · Tunable Current per channel: of 0-350mA for blue and green; 0-385mA for red
3. Separate Pulse Width Modulation per channel: Duty factor 0-100%.
4. Output voltage range of every channel provides enough voltage (plus a safety margin) to satisfy the maximum forward voltage specification in the Luxeon DCC data sheet (See also Data Sheet DS48).

5.2.2 Brightness Control of the LEDs

A three-channel output driver allows the control of the individual currents through the red, green, and blue strings of a Luxeon DCC light source. Proper current control provides constant brightness from the red, green and blue LED strings. This enables:

1. The initial setting of the white point and the luminance of the backlight in production. See Chapter 2.2
2. The end-user can set the white point and the luminance of the backlight, according to different usage and/or operating conditions.

3. Instantaneous setting of the brightness of the backlight according to image information. This gives the possibility to use the maximum brightness range of the LCD panel, even with very bright or dark images.
4. Reduction of power consumption of the backlight. In a LED driven backlight there is a linear correlation between luminance and power consumption. This makes it possible to set the power consumption at a very low level, which is contrary to a CCFL solution.

5.2.3 AM and PWM Dimming

There are two common methods to dim LEDs that are driven by a Constant Current Source:

1. Amplitude Modulation (AM).
2. Pulse Width Modulation (PWM).

AM

Amplitude Modulation (AM) varies the current that is driven through an LED string.

AM changes the brightness of the LEDs by reducing the current through the LEDs. That concept works well where the LED light output is well correlated to the nominal LED drive current via production flux testing. Lumileds bins 100% of their LEDs for flux at the nominal LED drive current. Thus there is a strong correlation between the brightness of the LEDs and its drive current in the range of the nominal LED current. However, when the drive current drops below 50% of the nominal LED current, then the light output is not as well correlated with the LED drive current anymore and thus the brightness variations from LED to LED tend to increase. Because of this it is not recommended to exceed an AM dimming ratio of 2:1.

Pulse Width Modulation

The Pulse Width Modulation (PWM) method drives the LEDs at their nominal current and varies the duty cycle to vary the average current through the LED to match the desired brightness. Because with PWM the LEDs are always driven at their nominal current, there are no correlation issues with the LED brightness and its drive current. This method provides for a linear relationship between the pulse width, the average LED current and the brightness of the LEDs.

Since LEDs have a turn-on time of less than 100ns, the dimming ratio for PWM driven LED systems is only limited by the rise or fall time of the driver. Theoretically the maximum dimming ratio is 1:35000, while in practice, a dimming ratio of 1:100 is more commonly used.

The rise and fall time of a driver output is defined as the time that is needed to increase the current from 10% of the peak current to 90% and vice versa. See Figure 5.2. The dimming is limited to the point where the pulse width becomes shorter than the rise or fall time of the driver.
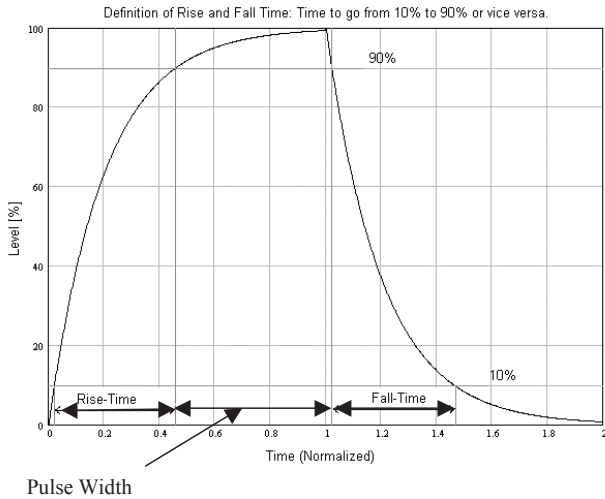
Definition of Rise and Fall Time: Time to go from 10% to 90% or vice versa.

Pulse Width

Figure 5.2 Rise and Fall Time in Pulse Width Modulation

AM and PWM

Lumileds recommends using AM only to set the correct white point in production. In practice this means that one color is typically set at its maximum, while the other two colors are used to set the correct white point. Once AM tuning is set, then the whole PWM range can be used for dynamic color control.

Customer requirements for the dimming ratio depend on the type of application in which the display is used. Table 5.1 shows typical dimming ratios for a number of applications.

Table 5.1   Dimming Ratios

Type of Application	Dimming Ratio:
Avionics	1: 35,000
Medical	1: 35,000
Automotive	1: 450
Outdoor Industrial	1: 50
Mobile	1: 50
Desktops	1: 2
TVs	1: 2

PWM Frequency

The PWM frequency of the backlight should be above 600Hz to avoid visual effects such as flickering and color banding (motion artifacts).

Pulse Positioning

Current fluctuations, due to on/off switching, in the PWM period can cause Electro-Magnetic Interference (EMI). When all LEDs are turned on at the same time, the variation in current at that moment is very high, see Figure 5.3 left situation. In order to reduce these fluctuations, it is better to start the individual color strings at different times, see Figure 5.3 right situation.
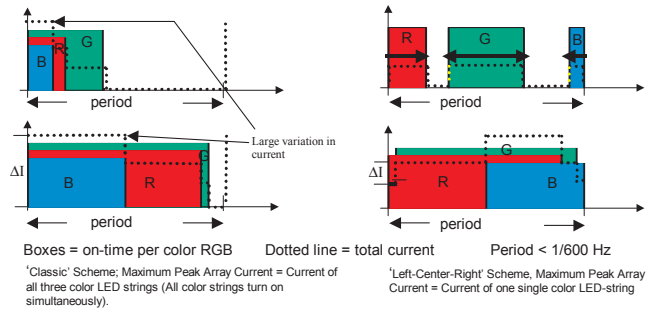

Boxes = on-time per color RGB   Dotted line = total current   Period < 1/600 Hz

'Classic' Scheme; Maximum Peak Array Current = Current of all three color LED strings (All color strings turn on simultaneously).

'Left-Center-Right' Scheme, Maximum Peak Array Current = Current of one single color LED-string

Figure 5.3 Pulse Positioning in PWM
(Left "Classic Scheme" and Right "Left-center-right" Scheme)

The two graphs at the top in figure 5.3 show a short duty cycle situation and the two pictures at the bottom show a long duty cycle situation. Boxes are presenting on time of the different color strings. The total current is drawn with the dotted line.

In the above figure in the left situation the current through the Red, Green and Blue string starts at the same time, requiring a high current peak at the start of every period. Such a scheme requires a current source that is capable of generating such a short rise-time current spike. Furthermore larger current spikes tend to also cause more unwanted Electro-Magnetic Radiation. In the right situation there is always only one string that changes in current at one point in time, causing less variation in current.

5.3 Light Output Control Over Temperature and Lifetime

5.3.1 Light Output Dependence on Temperature and Lifetime

Temperature Behavior

As mentioned in Chapter 4, the light output of a LED changes with the temperature of its junction and the rate of change is different for Red, Green and Blue LEDs. See Data Sheet DS48, Figure 5. This effect causes a shift in the ratios of light output for RGB and, as a consequence, a shift of the white point and a change in luminance. Compensation for this effect is required in order to maintain a stable white point and constant luminance. When the compensation is for a consistent change in junction temperature only, the typical duty cycles have to be changed according to Figure 5.4.
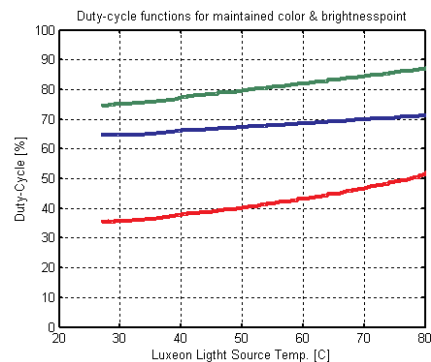

Figure 5.4 Example of Duty Cycles to Maintain White Point and Luminance

Lifetime Behavior

In addition to the temperature effect there is also a non-reversible degradation of LED light output over time. This is a small effect and thus adjustments for this second effect are optional. This behavior again is different from color to color and can cause a minor shift of the white point over time. These effects can be compensated for with Optical Feedback. Optical feedback provides a constant white point over the lifetime of the product, and is a unique feature of Luxeon DCC based backlights with a closed loop drive system.

Clipping

Because of the dependency of a LED light output on temperature, changes in the ambient temperature can create a situation in which the light source cannot produce the required amount of light for one of the three colors, even when the duty cycle is at 100%. This situation is called clipping. See Figure 5.5 Upper Graph.

There are three possible solutions to resolve this problem:
1. The clipped color stays at 100% and the two other colors are corrected as normal. This causes the brightness to be at a maximum, but the white point shifts a little bit.
2. The clipped color stays at 100% and the light output of the two other colors is reduced in a way that the white point is maintained. This causes an overall reduction in brightness. See Figure 5.5, Lower Part.
3. Design the application for maximum ambient temperature. With such a design the brightness will be lower at lower temperatures. Such an approach is not recommended.

The human eye is more sensitive to changes in white point than to changes in luminance. Thus keeping the duty cycle of the clipped color at 100% and adjusting the duty cycles of the other two colors to maintain the white point is therefore the preferred approach. Such an approach provides for a stable white point at a lower luminance. See Figure 5.5.
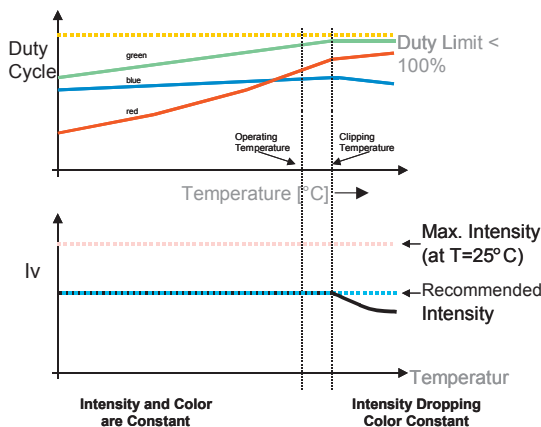

Figure 5.5 Clipping (Upper) and Solution for Clipping with Change in Backlight Brightness (Lower)

5.3.2 Optical Feedback and Thermal Feedback

There are two solutions that deal with the changing performance of the LEDs due to variation in temperatures and/or its loss of light over time.
1. Control by Temperature Feed Forward (TFF): A control feed forward loop reacts to a change in temperature and changes the duty cycles of the RGB LEDs accordingly.
   Note: TFF does not take into account the degradation of light output over time.
2. Control by Optical Feedback (OFB); A control feedback loop reacts to a change in wavelength and luminance and changes the duty cycles of the RGB LEDs accordingly.
   Note: For degradation performance of a driver and a sensor, please check their datasheets.

Note: TFF and OFB are optional. There are applications where changes of luminance and white point are not critical and therefore a cost/benefit analysis may show that these feedback features can be left out of the design.

Temperature Feed Forward (TFF)

The concept of TFF is based on the following principle: a temperature sensor (NTC resistor) on the MCPCB board measures the change in board temperature. A higher temperature of the LED will show a decrease in light output at a given rate (see data sheet). A combination of this effect and the NTC value change will result in an algorithm that calculates how the duty cycle of the RGB LEDs needs to be adjusted (based on a look up table) in order to compensate for this temperature effect. See Figure 5.7.
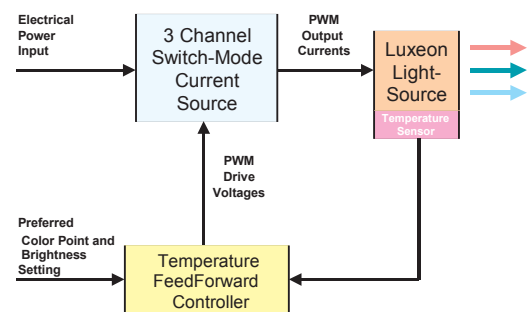

Figure 5.6 Overview of Thermal FeedForward

The MCPCB board temperature is measured with an NTC on the board of a Luxeon DCC light source. The thermal resistance junction to board may be used to determine the LED junction temperature from a measured board temperature.
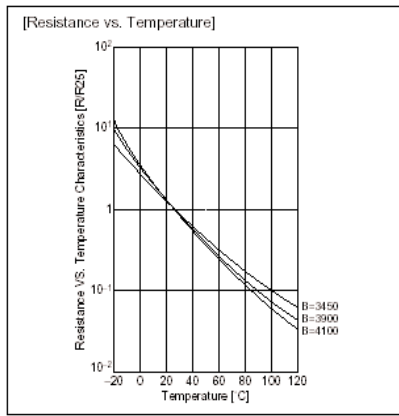
Figure 5.7 DC vs T and NTC Characteristics

Note: See the NTC (Murata) and Luxeon DCC datasheets. Temperature Feed Forward can be implemented by calculating the correction factors of the duty cycle with the temperature by measuring the temperature behavior of the LED and NTC.

Optical Feedback (OFB)

In an Optical Feedback system, a three-channel color sensor measures the optical energy in three different wavelength bands. A control algorithm translates these measured values into a set of PWM signals, which are used by the driver to adjust the corresponding duty cycles. See Figure 5.8 and Figure 5.1.
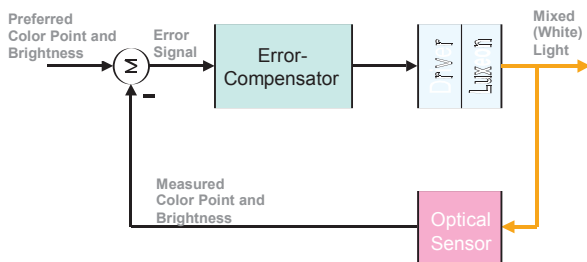

Figure 5.8 Principle of Optical Feedback

Optical Feedback offers a number of advantages in comparison to TFF. By measuring and calculating values for both wavelength and luminance, OFB corrects for behavior shifts due to temperature and loss of light over time. Due to this difference, in principle the OFB system is more accurate as a TFF loop. See Table 5.2, Comparison TFF and OFB, in the next section.

Sensor Types

Basically there are two types of optical sensor that can be used in an OFB system:

1. RGB sensor: This is the most obvious choice for customers. However, as LEDs have a small spectral distribution and the wavelength changes with the junction temperature, the accuracy of the sensor is limited.
2. XYZ-sensors: These sensors have the same transfer function as the human eye and behave in a similar manner. XYZ sensors have the highest level of accuracy and are,

therefore, recommended.
For information on where to place such sensors in a backlight system, please refer to Chapters 3.2.2 and 6.4

Signal Conditioning

Due to the small output signal of the sensor and, in most cases, its placement at a certain distance from the controller board, signal conditioning is needed to transport the signal from the sensor to the controller board. Signal conditioning can be accomplished by means of amplification, conversion (from current to voltage) or digitizing.

Table 5.2 Comparison of TFF and OFB

Solution	Correction Capability		Accuracy		Costs
	Brightness and White point variation with Operating Hours	Brightness and White point variation with Temp	Ave. White point variation over Operating Hours [delta u'v']	Ave. White point variation over Temp Δu'v' 25°C - 70°C [delta u'v']	
TFF	-	+	-	0,010	+
OFB	++	++	0,005	0,005	-

Chapter 6: Mechanical Design

This chapter describes the mechanical design guidelines of a LCD backlight in which Luxeon DCC products are used as light source. For the purposes of this application note, the FMWG is the only option observed. The following topics are being discussed:

· Optical structure and mechanical design
· Design aspects between light source and color mixing light guide
· Design aspects between color mixing light guide and main light guide
· Assembly of the Luxeon Light source

6.1 Optical Structure and Mechanical Design For the FMWG Example

The optical structure implemented in the mechanical design comprises the following main components. See Figure 6.1.

1. LED light source
2. Color mixing light guide
3. Main light guide
4. 90° mirror
5. 180° mirror
6. Reflective foil
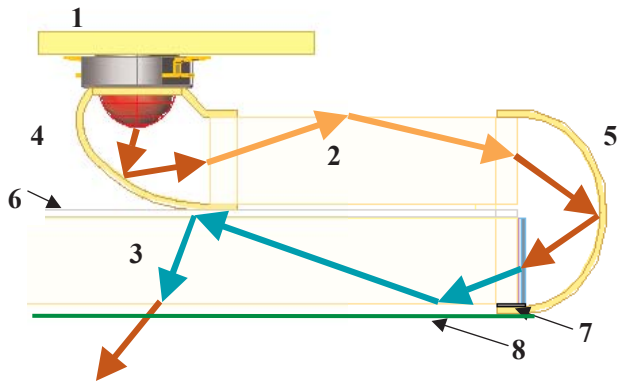7. Black Tape
8. LCD with films

Figure 6.1 Optical Design FMLG Concept

The light from the light source is coupled into the 90º mirror (4). From the mirror it is coupled into the color mixing light guide (2). The 180º mirror (5) directs this light into the main light guide (3), and the light is uniformly distributed via the reflecting foil (6) and coupled out into the LCD with films (8).

6.2 Design Aspects between Light Source and Color Mixing Light Guide

The light from the Luxeon light source is coupled into the color mixing light guide through a 90º mirror. The type of material, thickness of the material, and the shape of the mirror, play a significant role in the optical efficiency of the entire backlight system. See also Figure 3.8.

The in-coupling efficiency of the LED into the 90º mirror is determined by the dimension of the holes in the mirror, and the gap between the light source and the mirror (see Figure 6.4), and the thickness of the mirror material. See Figure 6.2.
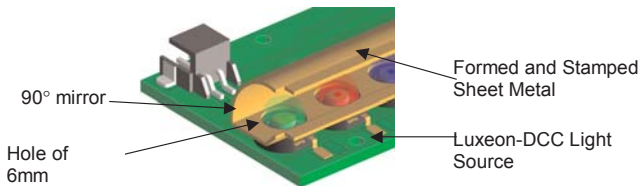

Figure 6.2 Placement of the 90º Mirror on Top of the Light Source

Hole Dimensions
It is NOT recommended to have the 90º mirror touch the LED lenses. The LED lens diameter is 5.6mm, therefore with a placement accuracy of +/-0.2mm the holes in the 90º mirror should be at least 6mm.

Gap
Make sure that there is a gap between the top of the LED housing and the bottom of the mirror. This gap should be as small as possible. This can be achieved by resting the mirror on the black housing of the LED, without putting force on the housing. A larger gap reduces the efficiency. See Figure 6.3.
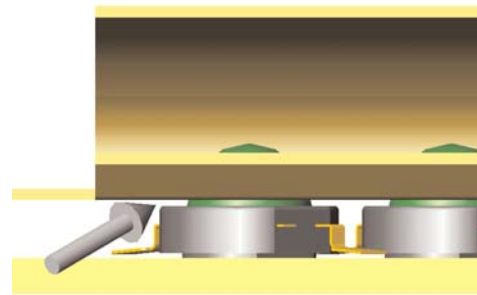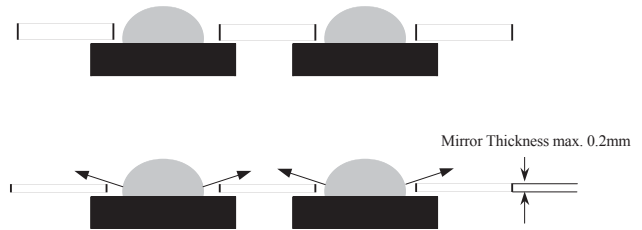

Figure 6.3 Gap Between LED Housing and Mirror

Thickness of the Mirror Material and Direct Light Extraction from Color Mixing Light Guide
The thickness of the mirror material plays an important role. The thicker the mirror, the more robust it is, but more light will scatter around when it couples from the LEDs to the mirror. It is recommended to have the mirror material as thin as possible without sacrificing the mechanically stability of the assembly. See the parts list at the end of this chapter for recommended thicknesses.

Moreover, it is not recommended that the back surface of the color mixing light guide touch the cover plate (part of assembly housing), since this will result in light extraction from the color mixing light guide. On this side of the color mixing light guide, the 90º mirror can act as a spacer and thus provide for an air gap. See Figure 6.4.
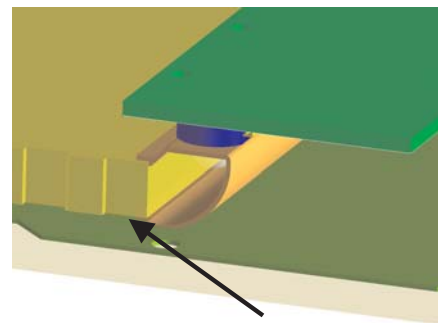

Figure 6.4 Air Gap between the Color Mixing Light Guide and the Cover Plate

6.3 Design Aspects between Color Mixing Light Guide and Main Light Guide

An 180º mirror redirects the light from the color mixing light guide into the main light guide. There are three important aspects to consider when it comes to optimizing performance

1. Align the mirror to the light guides so there is no light leaking between the main light guide, and the 180º mirror.
2. Prevent light from entering the space between the color mixing light guide, and the main guide.
3. Attention to the placement of a mirror that goes to the sides of the light guides and the 180º mirror. Any error made here may be visible on the main light guide.
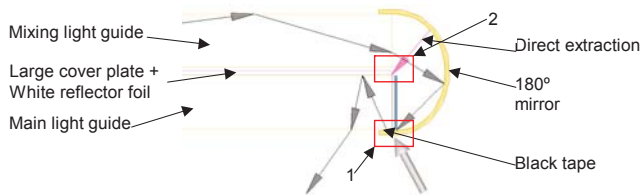

Figure 6.5 Forbidden direct extraction from the Main Light Guide (pointer 1 and 2)

Black Tape

Apply Black Vinyl Plastic Electrical tape to the 180º mirror or on the main light guide in the location shown in Figure 6.6 so that the edge of the tape aligns with the edges of the mirror. The width of the tape must be as wide as the non-elliptical curved part of the mirror (~1-2mm).

This tape absorbs the light that would otherwise enter the gap between the 180° mirror and the light guide, which would then result in a high intensity band just above the 180º mirror in the main light guide.
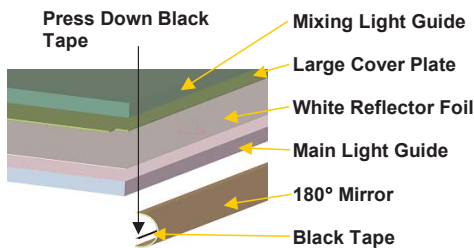

Figure 6.6 Applying Black Tape

If the black tape is too wide and covers parts of the elliptical mirror, it reduces the optical efficiency.

White Reflector Foil and Large Cover Plate

Place white reflector foil on the entire back of the main light guide, then place a cover plate on top of the reflector foil to prevent bending and curling of the foil.

Make sure that no light can enter the main light guide from the back. See also Figure 6.5. Light that enters the main light guide from the back extracts directly, causing a high intensity band on the main light guide. If the overlap of the cover plate into the 180º mirror is too large, then this has a negative

effect on the optical efficiency of the backlight. It is recommended to make an overlap of 0 to 0.5mm. See Figure 6.7.
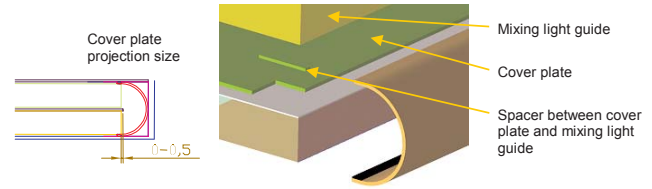

Figure 6.7 Overlap of Cover Plate and Positioning of Spacers

Spacers

Leave an air gap between the cover plate and the color mixing light guide to prevent direct extraction from the color mixing light guide. See Figure 6.8. If there is contact between the color mixing light guide and the cover plate, light will leave the color mixing light guide and bounce around. This will have a negative impact on the optical efficiency.

To make sure that there is a defined air gap between the cover plate and the color mixing light guide, place as many spacers as needed to avoid any contact between cover plate and color mix light guide. See Figure 6.7.
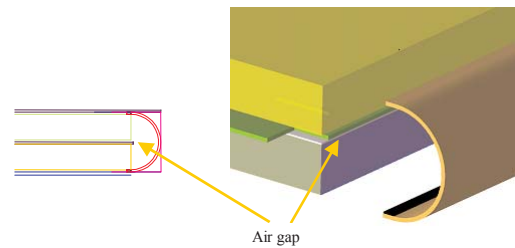
Figure 6.8 Air Gap between Cover Plate and Color Mixing Light Guide

Mechanical Interconnections

It is very important to make sure that all the optical components, the light guides and the mirrors, are aligned with each other. Cut outs may be used as alignment features and are recommended to help align the light guides and mirrors to each other and to other parts in a supporting frame. Failure in proper alignment of the different parts may result in unwanted colour stripes in the main light guide. The mechanical cut outs in the color mixing light guide, and the main light guide, have to be located at a position far away from the 180º mirror to prevent unwanted light extraction. It is also important to make these cut outs as small as possible. See Figure 6.9.

Figure 6.9 Example of Cut Out alignment feature in the Color Mixing Light Guide

Mirror Side Reflectors

In order to prevent light leaking from the side of the 180°
mirror, a mirror should be placed on both ends of the 180°
mirror. These mirrors close the optical opening between the
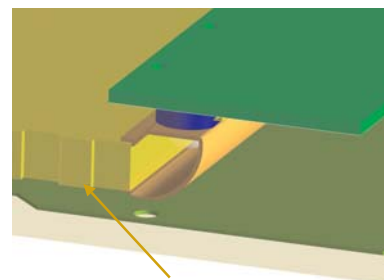main light guide, the color mixing light guide, and the 180°
mirror.

The effect of misalignment of the side reflectors in the 180°
mirror is very large. If the side reflectors are misaligned with
the light guides a color mark will be visible on the front of the
screen.

6.4 Design Aspects for Mounting the RGB Sensor

The preferred position for the RGB-sensor is on the opposite
side of the in-coupling side (opposite side of 180° mirror). On
this side the edge of the main light guide is covered with a
specular reflective tape. A small hole on this side serves as a
receptive for the Optical Feedback sensor. This hole has to
be as small as possible to prevent shadowing effects. See
also Chapter 3.2.2 Optical Feedback Sensor.

6.4 Assembly of the Luxeon Light Source

The Luxeon light source module needs to be mounted to a
flat aluminium heat sink with a surface roughness of less
than 10mm (including anodisation). This can be done by
screwing the heat sink to the light source module or by
screwing the light source module to the heat sink.

For assembling the heat sink to the Luxeon DCC light source
module (not Luxeon DCC module to heat sink) follow these
recommendation:
1. Use self-tapping screw M2.5.
2. Provide for holes in the board (Ø 2.1mm).
3. Provide for holes in the heat sink (Ø 2.7mm).

Self tapping screw
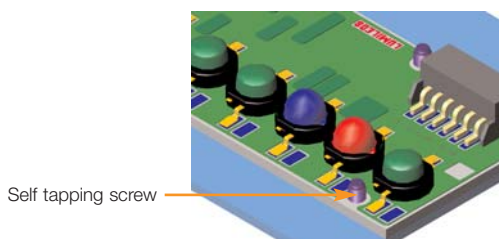
Figure 6.10 Assembly of the Heat Sink to the Luxeon Light Source

Note: It is critical to only use the holes provided in the
Luxeon DCC light source. Adding additional holes
will likely sever electrical traces causing the array not
to function.

For assembling the Luxeon DCC light source module to the
heat sink (not heat sink to Luxeon DCC module) follow these
recommendations:
1. Screws M2 with or without nut.
2. Use holes in the board (Ø 2.1mm).
3. Use holes in the heat sink M2 or Ø 2.3mm.
4. The M2 screws need to have a screw head of ~ Ø 3.6mm.

Figure 6.11 Assembly of the Luxeon Light Source to the Heat Sink

In both cases the maximum torque is 0.3 Nm.
The heat sink, on which the light source module is assem-
bled, must be positioned into a supporting frame such that it
aligns with the 90° mirror.

6.6 Bill of Materials for Backlight Module

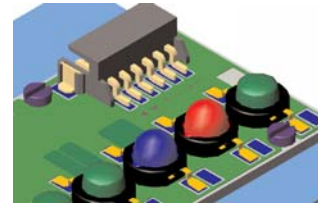| Part	Material (or Equivalent)	Info
90° mirror	Enhanced Specular Reflector film (ESR) on stainless steel plate (~0.3 mm), from 3M Vikuiti, thin polymer film, > 98% reflectance visible spectrum	http://selector.3m.com/osd_vikuiti/ss.asp?FAM=film
Color mixing light guide	PMMA plate: Perspex™ 00, casted plate, from Lucite	http://www.perspex.co.uk/products/specifications.htm - table4
	PMMA granulate: Diakon™ MG 102K	http://www.diakon.com/sboutus/facts/index.htm
180° mirror	Enhanced Specular Reflector film (ESR) on stainless steel plate	
Main light guide	PMMA plate: Perspex™ 00, casted plate, from Lucite	http://www.perspex.co.uk/products/specifications.htm - table4
	PMMA granulate: Diakon™ MG 102K	http://www.diakon.com/sboutus/facts/index.htm
		http://www.luciteinternational.com/
White reflector sheet	E60L Polyester film ~0.2mm, measured reflectivity at normal incidence: 95%; diffuse scattering with specular component	http://www.toray.co.jp/
Diffusers films	Weak diffusers: Opalus #100 BMU1S from Keiwa on poly(ethylene terephthalate) (PET) film	http://www.keiwa.co.jp/atac/index.html
BEF III -T from 3M- Vikuiti		http://selector.3m.com/osd_vikuiti/ss.asp?FAM=film
Aluminium heat sink	Alloy 1050A IRC number	High thermal conductivity aluminum
	S60 from Showa denko. Thermal conductivity is 218 W/mK	

Appendix A: Definitions and Concepts

This Annex contains definitions of terms used in this Application Note for Luxeon DCC LED backlight applications

AR Coating
Anti-reflection coating, suppresses the reflection of light on a surface, and increases the in coupling of light into a medium.

Aspect Ratio
The ratio between the height and width of a display. Most common ratios are 3:4 and 9:16.

Attenuation Rate
The decrease of light intensity inside a medium, normally expressed in %/inch or %/cm.

Backlight
Illumination from behind the subject in a direction substantially parallel to a vertical plane through the optical axis of the viewer.

Brightness Enhancement Film (BEF)
Optical film that enlarges the intensity of light by bending the light into a smaller vertical or horizontal angle.

Black Body Locus (Planckian Locus)
The locus of points on a chromaticity diagram representing the chromaticities of black bodies at various temperatures.

Brightness
Brightness is generally used as the perceptive impression of luminance. No units are available.

Candela (cd)
The unit of luminous intensity Iv, which corresponds to the luminous flux in lumens per unit solid angle (lm/sr).

Chromaticity
Describes the 'color' of the light.
  · Space
      · Color Space, where all perceived colors are described, most common are 1931 xy-Color Space and 1976 Uniform Color Space (UCS)

Color
- **Space**
  - See: Chromaticity Space
- **Gamut**
  - Area in a Chromaticity Space, describing the possible colors generated by a system, most known are NTSC and EBU Color Gamut.
- **Spectrum**
  - Distribution of radiometric electromagnetic energy over the wavelength

Contrast
Contrast is the ratio between the maximum luminance and the minimum background luminance that can be generated on a display. Contrast generally depends on the location on the display and on the viewing direction. Contrast is defined by the following formula:

$C = \{L_{(information)} - L_{(background)}\} / L_{(background)}$

Contrast (C) and Contrast ratio (CR) are related by the formula: $C = CR - 1$

Contrast Range
The ratio between the highest luminance and the lowest luminance in a movie scene.

Contrast Ratio
The ratio between the information luminance and the background luminance:

$CR = L_{(information)}/L_{(background)}$

Contrast ratio in high ambient light illumination is defined as CR_d for diffuse (skylight) illumination and CR_h for direct sunlight illumination.

Correlated Color Temperature (CCT)
The absolute temperature of a black body whose chromaticity most nearly resembles that of the light source. See reference AB 08.

CRT
Cathode Ray Tube
- **Phosphors**
  - Set of defined phosphors to generate the correct NTSC or EBU gamut

Depolarizing Brightness Enhancement Film (DBEF)
Optical film that re-uses the light that is lost by the LCD's polarization of the in-coupled light.
- Advantage: DBEF enables a smaller light source to yield the same intensity as a larger light source without DBEF.
- Disadvantage: expensive.

Dimming Ratio
Ratio between the lowest and highest achievable brightness of a system.

Direct Extraction
Rays that enter the light guide outside the TIR angle and directly extract from it causing brightness variations.

Dominant Wavelength
Wavelength of pure saturated color that is perceived by the human eye as the same color as the xy-co-ordinates of the light emitted by the light source (see reference AB 08).

Duty Cycle
Percentage describing the ratio between the on-period of a signal divided by the total period. Therefore the maximum duty cycle is 100%.

Efficacy
Efficiency of a light source describing the luminous flux versus electrical power ratio, expressed in lm/W.

Efficiency
The efficiency of a backlight can be expressed in different ways. The most direct expression for the efficiency is the ratio between the 'luminous flux out of the backlight' and the 'luminous flux out of the LEDs. This is a **lm / lm** ratio.

An alternative way to express efficiency is by means of the ratio between the 'optical power out of the backlight' and the 'optical power out of the LEDs'. This is a **W /W** ratio and has the same value as the above-mentioned lm / lm ratio when there is no dispersion in the backlight optics, which is usually the case.

Since the output of a backlight is usually not judged by its output in terms of lumens, but rather in terms of luminance, other useful metrics for efficiency are **nits/lm** and **nits/W**. In both cases the nits represent the luminance as observed normal to the backlight. Nits/lm is a measure for the efficiency of the optical system excluding the LEDs, whereas nits/W is a measure for the efficiency of the entire backlight.

EEW-Point
Equal Energy White point, is the point where all three tristimulus values are receiving the same energy. Also known as Illuminant E.

Eye Sensitivity Curve
Curve describing the relative brightness sensitivity of the human eye over the wavelength expressed in lm/W. The maximum is 583 lm/W at 555nm.

Fall Time
Time a signal changes from 90% to 10% of its value. See also Rise-Time.

Flux
Total amount of light from a light source expressed in lm.

Heat Transfer Coefficient
Material Constant describing the energy transfer from the surface to ambient, expressed in W/m^2K.

Illuminant E
See EEW-point

Intensity
Intensity is flux from a light source per solid angle. The measurement distance is larger than 10x the source size, so that the light source can be considered as a point source. The unit for intensity is cd (= candela = lumen / steradian).

Isotemperature Line
Line in a Chromaticity Space where all points have the same Correlated Color Temperature (CCT).

Junction
The layer inside the LED die, where the actual generation of photons takes place, also known as the active layer or epi layer.
- Temperature
  - Temperature of the active layer. This influences the Forward Voltage, Spectral behavior and Flux of a LED

LED
Light Emitting Diode. Semiconductor Device that converts electrons into photons, and behaves electrically as a diode.

Light
Visually evaluated radiant energy. Multiplying the energy radiated at each wavelength by the spectral luminous efficacy data for that wavelength and adding the results accomplish the evaluation.
- Guide
  - A medium with a special from that captures the light inside, as the light is inside the Total Internal Reflection (TIR) Angle.
    - o Mixing - Flat plate in which the mixing of the light of the three primary colors to white takes place.
    - o Main - Flat plate in a backlight that distributes the light over the surface and couples it out towards the LCD panel.

Lumen (lm)
Total amount of visible light emitted from a light source.

Luminance
Luminance is the luminous flux per solid angle per area. The unit for luminance is cd/m^2. An alternative name for cd/m^2 is nit; the English unit is footlambert (fL). [1 fL = 3.4263 cd/m^2].

The luminance of a source or surface generally depends on the viewing direction and on the location on the source. The luminance of a backlight usually refers to the luminance perpendicular to the surface and in the center of the backlight.
- Average
  - The average luminance is determined by measuring a number of points of a backlight and averaging the values.
- Peak
  - The maximum luminance of all measured points

Luminous Flux
Luminous Flux is equivalent to Optical Power. Luminous Flux is Optical Power, radiometric flux spectrally weighted with the visual response curve of the eye. The unit for luminous flux is lm (= lumen).

Luminous Intensity (cd = lm/sr)
Luminous flux per unit solid angle in a given direction; the quotient of the luminous flux on an element of surface normal to that direction by the solid angle (in steradians) subtended by the element as viewed from the source.

Nit (nit = cd/m²)
Unit of photometric brightness (luminance) equal to one candela per square meter.

Optical Feedback (OFB)
System where the actual chromaticity of a light source is measures with a sensor, and compared with the set point value. The feedback loop changes the chromaticity such that the difference between set point value and actual value is as small as possible.

Optical Power
Optical Power is the energy per second in a beam of light. Optical Power or radiometric flux is expressed in Watts.

Pixel (px)
A pixel (picture element) is the smallest element of a display surface capable of reproducing the full range of luminance and colors. Often composed of sub-pixels (R,G,B) or dots.

PMMA
Transparent Material used for light guides.

Primary Colors
The primary colors in color adding systems, light mixing systems, are Red, Green and Blue.

Refraction Index
Material constant describing the refraction of the light at surfaces.

Rise Time
The time a signal needs to rise from 0% to 90% of its value.

Spectrum Locus
The line connecting all monochromatic (single wavelength) points in the xy and u'v' Chromaticity Diagram, together with the Purple Line, it is the outside of the Color Space described.

Steradian (Unit Solid Angle)

A solid angle subtending an area on the surface of a spherical equal to the square of the sphere radius. A sphere has a solid angle of 4II sr.

Viewing Angle

The viewing angle is the angle range at which a backlight can be observed, maintaining a certain minimum contrast ratio. Usually the viewing angle is specified in two directions: horizontal and vertical. The luminance drop at the viewing angle limits is often not specified.

XYZ Sensor

Sensor with a similar behavior as the human eye with the direct tristimulus values as output. The types of sensors have Red, Green and Blue filters similar to that of the human eye.

Abbreviations:

α	Heat transfer coefficient
AlInGaP	Aluminum Indium Gallium Phosphide
AM	Amplitude Modulation
AR	Anti-reflection (coatings)
CAD	Computer Aided Design
CCFL	Cold Cathode Fluorescent Lamp
CCT	Color Correlated Temperature
CFD	Computational Fluid Dynamics
CRT	Cathode Ray Tube
DBEF	Depolarizing Brightness Enhancement Films
DCC	Dynamic Color Control
EBU	European Broadcasting Union
EMI	Electro Magnetic Interference
ESR	Enhanced Specular Reflector film
FMLG	Folded Mixing Light Guide
FOS	Front-of-Screen
InGaN	Indium Gallium Phosphide
LCD	Liquid Crystal Display
MCPCB	Metal Core Printed Circuit Board
NTC	Negative Temperature Coefficient Resistor
NTSC	National Television System Committee
P_{diode}	Dissipated Power by the LED
PWM	Pulse Width Modulation
RGB	Red, Green, Blue
R_{th}	Thermal Resistance
SMPS	Switch Mode Power Supplies
TBE	Total Backlight Efficiency
TFF	Temperature Feed Forward
TIR	Total Internal Reflection
T_j	Junction Temperature
UCS	Uniform Color Space
UV	Ultra Violet

Appendix B: Calculation of Red, Green and Blue Fractions

This example calculates the needed fractions of Red, Green and Blue flux, with given Red, Green and Blue xy-coordinates, to produce a given 9000K White point, with a given xy-point:

$$\begin{pmatrix} f_R \\ f_G \\ f_B \end{pmatrix} = \begin{pmatrix} \dfrac{x_R}{y_R} & \dfrac{x_G}{y_G} & \dfrac{x_B}{y_B} \\ 1 & 1 & 1 \\ \dfrac{1-x_R-y_R}{y_R} & \dfrac{1-x_G-y_G}{y_G} & \dfrac{1-x_B-y_B}{y_B} \end{pmatrix}^{-1} \begin{pmatrix} \dfrac{x_W}{y_W} \\ 1 \\ \dfrac{1-x_W-y_W}{y_W} \end{pmatrix}$$

(1) ← Part A → ← Part B →

The explicit form of the matrix inverse is as follows:

$$A^{-1} = \begin{pmatrix} \dfrac{((-1+x_G)\,y_B-(-1+x_B)\,y_G)\,y_R}{x_R\,(-y_B+y_G)+x_G\,(y_B-y_R)+x_B\,(-y_G+y_R)} & \dfrac{(-x_G\,(-1+y_B)+x_B\,(-1+y_G))\,y_R}{x_R\,(y_B-y_G)+x_B\,(y_G-y_R)+x_G\,(-y_B+y_R)} & \dfrac{(x_G\,y_B-x_B\,y_G)\,y_R}{x_R\,(-y_B+y_G)+x_G\,(y_B-y_R)+x_B\,(-y_G+y_R)} \\ -\dfrac{y_G\,((-1+x_B)\,y_B-(-1+x_B)\,y_R)}{x_R\,(-y_B+y_G)+x_G\,(y_B-y_R)+x_B\,(-y_G+y_R)} & \dfrac{y_G\,(-x_R\,(-1+y_B)+x_B\,(-1+y_R))}{x_R\,(-y_B+y_G)+x_G\,(y_B-y_R)+x_B\,(-y_G+y_R)} & -\dfrac{y_G\,(x_R\,y_B-x_B\,y_R)}{x_R\,(-y_B+y_G)+x_G\,(y_B-y_R)+x_B\,(-y_G+y_R)} \\ -\dfrac{y_B\,((-1+x_G)\,y_G-(-1+x_G)\,y_R)}{x_R\,(y_B-y_G)+x_B\,(y_G-y_R)+x_G\,(-y_B+y_R)} & \dfrac{y_B\,(-x_R\,(-1+y_G)+x_G\,(-1+y_R))}{x_R\,(y_B-y_G)+x_B\,(y_G-y_R)+x_G\,(-y_B+y_R)} & -\dfrac{y_B\,(x_R\,y_G-x_G\,y_R)}{x_R\,(y_B-y_G)+x_B\,(y_G-y_R)+x_G\,(-y_B+y_R)} \end{pmatrix}$$

Example:

For a light source with given color coordinates of R, G, and B LEDs, calculate the flux fractions needed to produce 9000K white with:

Backlight White coordinates:
x_W=0.287 y_W=0.296

LED coordinates:
Red coordinates: x_r = 0.700 y_r = 0.299
Green coordinates: x_g =0.206 y_g = 0.709
Blue coordinates: x_B = 0.161 y_b = 0.020

Solution:
Substituting the x and y values of Red, Green and Blue LEDs results in the numerical matrix:

$$A = \begin{pmatrix} 2.3411 & 0.2906 & 8.0500 \\ 1.0000 & 1.0000 & 1.0000 \\ 0.0033 & 0.1199 & 40.9500 \end{pmatrix}$$

The inverse of this matrix is:

$$A^{-1} = \begin{pmatrix} 0.4825 & -0.1292 & -0.0917 \\ -0.4838 & 1.1325 & 0.0675 \\ 0.0014 & -0.0033 & 0.0242 \end{pmatrix}$$

Substituting the xw and yw coordinates of the white point results in the column vector:

$$B = \begin{pmatrix} 0.9696 \\ 1.0000 \\ 1.4088 \end{pmatrix}$$

Finally, multiplying the inverted matrix by the column vector, results in the flux fractions:

$$\begin{pmatrix} f_R \\ f_G \\ f_B \end{pmatrix} = A \otimes B = \begin{pmatrix} 0.2094 \\ 0.7584 \\ 0.0322 \end{pmatrix}$$

Or in words:
To produce 1 lm of white light (9000K) with coordinates (x, y) = (0.287, 0.297) with the above mentioned Red, Green and Blue LEDs the following fractions are needed:
Red = 0.21 lm
Green = 0.76 lm
Blue = 0.03 lm

Appendix C: Attenuation Rates for Various PMMAs

This section shows the attenuation rate for a large number of different PMMAs. Lumileds regards 1% per inch as an acceptable rate.
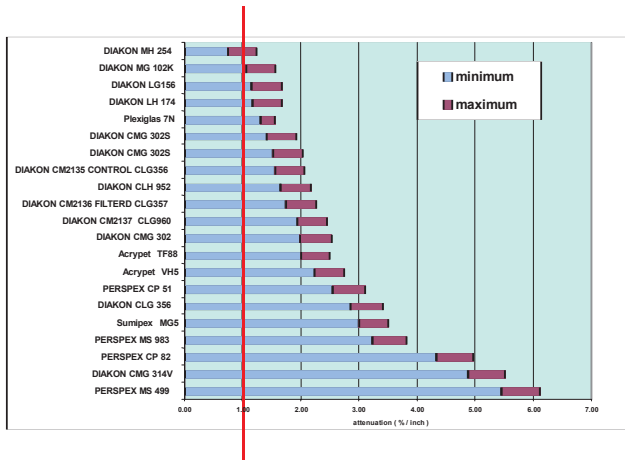

Figure C1 Attenuation Rates (%/inch) for Different PMMAs

Please note that the choice of preferred PMMA material should take into account the following fact: because a Luxeon-RGB light source does not emit any light in the ultra violet (UV) region, the material does not require a UV absorber. In a CCFL-based backlight the UV light can damage the LCD when no UV absorber is used.

Appendix D: Thermal Path Calculation Method

The following tables show the calculation of the total thermal resistance through the front and the back of the flat plate design. Please note that the combined effect of convection and radiation is expressed as the heat transfer coefficient.

Table D1 Thermal Path Front

Layer	Thickness (mm)	Conductivity (W/mK)	Area m²	Effective Resistance [°C / W]
Air gap 1	0.1	0.03	0.08	0.042
PMMA 1	6	0.2	0.08	0.375
Air gap 2	0.1	0.03	0.08	0.042
PMMA 2	6	0.2	0.08	0.375
Foils	1	0.1	0.08	0.125
Panel	2	0.1	0.08	0.250
Plate to air		Estimated: 10W/m²K	0.08	1.250
TOTAL R_{th} front				2.458

Table D2 Thermal Path Back

Layer	Thickness (mm)	Conductivity (W/mK)	Area m²	Effective Resistance [°C / W]
Plate to air		Estimated: 10W/m²K	0.08	1.25
R_{th} back				1.25

The Figure D1 represents the Thermal Path Layout.

Thermal Path via backside:
1. Heat sink

Thermal path via front side:
1. Air gap 1
2. PMMA mixing guide
3. Air gap 2
4. PMMA main LG
5. Foils
6. LCD Panel

R_{th} front

P_d

R_{th} back

P_d = Electrical Input Power Light source
R_{th} front = Thermal Resistance Front
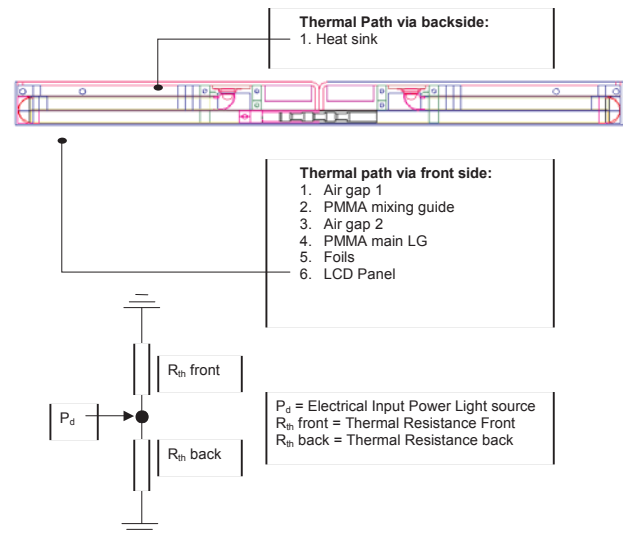R_{th} back = Thermal Resistance back

Figure D1 Thermal Path Layout.

Appendix E: Contact Details of Component Suppliers

Electrical Components

Switch Mode Power Supplies for Luxeon DCC, plug & play, are available from the following partners:

· Delta Electronics: www.deltaww.com

186 Ruey Kuang Road, Neihu, Taipei 114, Taiwan, R.O.C

· Intersil: www.intersil.com

675 Trade Zone Blvd., Milpitas, CA 95035, U.S.A.

· Toko: www.toko.com

18 Oaza Gomigaya, Tsurugashima-shi, Saitama, 350-2281 Japan

· Japan Aviation Electronics Industry, Limited

3-1-19, Aobadai, Meguro-ku, Tokyo, 153-8539 Japan
http://www.jae.co.jp

Optical Components

Optical sensors are available from the following partners:

· Agilent Technologies: www.agilent.com

Bayan Lepas Free Industrial Zone 11900, Penang, Malaysia

· Hamamatsu Photonics: www.hpk.co.jp/Eng/main.htm

1126-1, Ichino-cho, Hamamatsu-shi, Shizuoka, 435-8558 Japan

Appendix F: Selection Tables and Expected Thermal Resistances for Different Screen Configurations

Selection Method:

1. Determine screen size and aspect ratio
2. Choose placement of light source: Left/Right or Top/Bottom
3. Read Part number to be used
4. Go to Table F2: Use selected light source and aspect ratio
5. Read estimated thermal resistance of flat plate

Use Table F3 and result of step 5, to calculate the maximum expected heat sink temperature @ 9000K and $T_j = 85°C$

Table F1   Approximate Screen Sizes (in inches) at 4:3 and 16:9 Aspect Ratio, Luxeon DCC Range at Different Light Source Configurations

Luxeon DCC Type	Diagonal Screen Size (inch) (Equals size of flat plate)			
	Top/Bottom Placement		Left/Right Placement	
	4:3	16:9	4:3	16:9
LXHL-MDAA	5	4.5	7	8
LXHL-MDBA	8	7	10	12
LXHL-MDCA	11	10	15	18
LXHL-MDDA	15	14	20	25
LXHL-MDEA	18	16.5	24	29

Table F2   Typical Thermal Resistance (K/W) of a Flat Plate Based Cooling Solution of Black Anodized Aluminium

Luxeon DCC Type	Thermal Resistance [K/W]			
	Top/Bottom Placement		Left/Right Placement	
	4:3	16:9	4:3	16:9
LXHL-MDAA	8.6	11.9	4.4	3.8
LXHL-MDBA	3.4	4.9	2.2	1.7
LXHL-MDCA	1.8	2.4	1	0.75
LXHL-MDDA	1	1.2	0.5	0.4
LXHL-MDEA	0.66	0.9	0.4	0.3

Table F3   Typical LED Light Source Power (W) for 9000 K CCT at $T_j = 85°C$

Luxeon DCC Type	Typical Power [W]
LXHL-MDAA	10.3
LXHL-MDBA	14.9
LXHL-MDCA	24.2
LXHL-MDDA	33.6
LXHL-MDEA	41.3

Appendix G: Calculation of the Flux at Given Board Temperature

This annex shows the calculation of the expected flux per color, of a given light source, at a given board temperature.
Note: In Chapter 2.4 the reverse calculation is made: what is the needed flux at $T_j=25°C$, with a given required flux at a specific board temperature.

With the use of Figure G1 (or Figure 5 of Data Sheet 47) the total flux per color of a given light source at a given board temperature can be calculated. This calculation follows three steps:

1. Calculate the junction temperature at the given board temperature, with the use of the thermal model in Chapter 4.
2. Calculate the flux ratio between Tj = 25 °C and the calculated junction temperature with Figure G1.
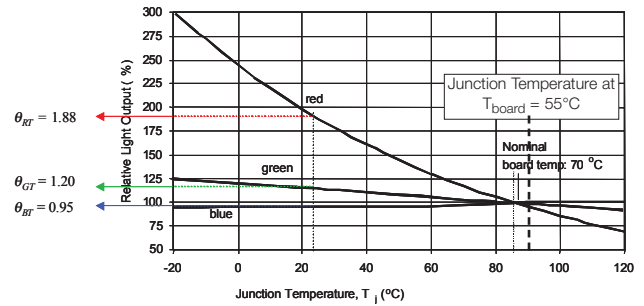3. Multiply the given flux at Tj = 25°C in DS47 with the ratio from step 2.

Figure G1   Junction Temperature vs Photometric Light Output

Example:

Calculate the flux of the Red LEDs of the LXHL-MGAA at a board temperature of 55°C.

1. The thermal resistance for junction-to-board is 1.50 K/W and the typical dissipated power is 33.6W. With the use of formula 4.1 the following is found:

$$R_{th-junction-to-board} = \frac{\left(T_{junction} - T_{baord}\right)}{P}$$

$$1.50°C/W = \frac{T_{junction} - 55°C}{33.6W}$$

$$T_{junction} = 55°C + (1.50 * 10.3)°C = 70.5°C$$

2. The ratio is calculated between the flux at $T_j=25°$ and $T_j = 70.5$ °C is:

$$\frac{\theta_{Red,Tj=55°C}}{\theta_{Red,Tj=25°C}} = \frac{120\%}{188\%} = 0.64$$

3. Now the total flux at $T_j=25°C$ at $I_f=350mA$ is multiplied with the ratio:

$$\theta_{Red,T_j=55°C} = \theta_{Red,T_j=25°C} \times \frac{\theta_{Red,Tj=55°C}}{\theta_{ed,Tj=25°C}} = 118lm \times 0.64 = 75.3lm$$

I=350mA

Note: Additional information on thermal design can be found in Application Brief AB05 and in Annex C.

Company Information

Luxeon is developed, manufactured and marketed by Lumileds Lighting, U.S., LLC. Lumileds is a world-class supplier of Light Emitting Diodes (LEDs) producing billions of LEDs annually. Lumileds is a fully integrated supplier, producing core LED material in all three base colors (Red, Green, Blue) and White. Lumileds has R&D development centers in San Jose, California and Best, The Netherlands and production capabilities in San Jose, California and Malaysia. Lumileds Lighting is a joint venture of Agilent Technologies and Philips Lighting and was founded in 1999. Lumileds is pioneering the high-flux LED technology and bridging the gap between solid-state LED technology and the lighting world. Lumileds is absolutely dedicated to bringing the best and brightest LED technology to enable new applications and markets in the Lighting world.

Lumileds may make process or materials changes affecting the performance or other characteristics of our products. These products supplied after such changes will continue to meet published specifications, but may not be identical to products supplied as samples or under prior orders.

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