DEVELOPMENT OF VARIOUS CORNER-LIT BACKLIGHTING CONCEPTS IN AN ADVANCED SMART LED TV

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by

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DEVELOPMENT OF VARIOUS CORNER-LIT BACKLIGHTING CONCEPTS IN AN ADVANCED SMART LED TV

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For my parents

ABSTRACT

CCFL (Cold Cathode Florescent Lamp) based LCD (Liquid Crystal Display) TVs are replaced by Smart LED TVs with the help of recent improvements of the LED (Light Emitting Diode), electronics and information technologies. Electronics and LED improvements make connected, slimmer, fancy looking, wide color gamut, high luminance and energy efficient TV design possible. Optical design parameters are totally changed with LEDs' directional light emission. The efficacy improvement of LED chips helps decrease the number of LEDs and power consumption in the BLU (Backlight Unit) of the LED TVs. More than 50% of the TV power is consumed by the BLU. In addition to power consumption, manufacturability and cost level of TVs also highly depend on the BLU. Therefore LED structure of the TV takes a very important role in efficient TV design.

The key point in decreasing the power consumption, cost level and manufacturability difficulty is decreasing the number of LEDs. In conventional BLUs, LEDs are placed at the four edges of the TV. However, the current LED placement technique has reached its limits. It is not easy to decrease the number of LEDs without any visual defect. Therefore, a new design concept should be studied. The corner placed LED (corner-lit) structure is the main focus of this study. There are optical and thermal design obstacles to overcome in this concept. The light distribution of the LEDs which are located at a specific point of the system is the most critical parameter in terms of optical design. In addition, the cooling mechanism of the high power LEDs in a small volume closure which allows only thermal conduction is the bottleneck in terms of thermal management.

The market and design trend overview of LED TVs is explained in the first part of the work. After that, optical and thermal design objectives are determined for the corner-lit LED BLU. LC cell characterization and optical film structure experiments are performed, in order to

increase the optical efficiency of the BLU. Then various types of high power LEDs are investigated to implement into the design. Computational optical simulations are performed to be able to understand the optical achievements of different LED types and placements. In the next step, a new high efficiency cooling system is characterized in computational fluid dynamics (CFD) software. After the computational studies, critical design parameters are determined for both optical and thermal structure. Possible future studies are also proposed in order to overcome the estimated design difficulties.

ÖZETÇE

Son yıllarda elektronik, bilgi işlem ve LED teknolojilerinde yapılan gelişmeler sayesinde Akıllı LED TV'ler CCFL (Floresan Lamba) bazlı LCD TV'lerin yerini aldılar. Internet bağlantılı, ince, şık görünümlü, geniş renk gamına sahip ve parlaklığı yüksek TV tasarımlarını LED ve elektronik alanındaki ilerlemeler mümkün kılmaktadır. Işık kaynağının CCFL'den LED'e geçmesi ile ışık emisyonu tek yönlü hale gelmiş ve tüm optik tasarım parametrelerini değiştirmiştir. LED'lerin verimliliğinin zaman içerisinde artaması ile birlikte LED TV arkaışık ünitesi tasarımlarında kullanılan LED sayısı azalmış ve güç tüketim miktarı da düşmüştür. TV güç tüketiminin % 50'sinden fazlasını arkaışık ünitesinin oluşturduğu düşünüldüğünde bu tasarımların önemi ortaya çıkmaktadır. Güç tüketimine ek olarak LED TV'lerin üretim zorluk seviyesi ve maliyet yapısı büyük oranda arkaışık ünitesi ile bağıntılıdır. Bu sebeplerden dolayı TV'lerde kullanılan LED yapıları verimlilikleri üzerinde önemli rol oynamaktadır.

Güç tüketimi, maliyet ve üretim zorluğunun azaltılmasında tasarımdaki kilit nokta LED sayısının azaltılmasıdır. Marketlerde bulunan standart LED TV'lerin arkaışık ünitelerinde LED'ler dört kenara dizilmektedir. Fakat, mevcut kenara dizme yöntemi tasarımsal olarak limitlere ulaşmıştır. Herhangi bir görsel problem yaratmadan LED sayısını azaltabilmek çok zordur. Bu sebeple yeni bir tasarım konsepti üzerine çalışılması gerekmektedir. Köşeye yerleştirilmiş LED'ler ile oluşturulacak arkaışık ünitesi bu çalışmanın ana odağıdır. Bu arkaışık ünitesi konseptinde üzerine çalışma yapılıp çözülmesi gereken termal ve optik tasarım zorlukları bulunmaktadır. TV'nin köşe noktasına yerleştirilmiş olan LED'lerin arkaışık ünitesi içerisinde eş dağılım koşullarını sağlayabilmesi optik tasarım açısından en kritik noktadır. Köşe noktaya yerleştirilen yüksek güç tüketimli LED'lerin, kapalı ve küçük

bir hacim içerisinde bulunmasından dolayı sadece ısıl iletim ile soğutulabilmesi de termal tasarım açısından zorluk yaratmaktadır.

LED TV market ve tasarım yönelimleri çalışmanın ilk bölümünde açıklanmıştır. Daha sonrasında çalışmada bahsi geçen temel kavramların anlatımı ve köşeden aydınlatmalı LED TV için optik ve termal tasarım hedefleri tespit edilmiştir. Arkaışık ünitesinin optik verimliliğini arttırmaya yönelik LC (liquid crystal) hücre analizleri ve optik film yapısını belirlemek için yapılan deneyler ve sonuçları değerlendirilmiştir. Köşe aydınlatmada kullanılabilecek farklı yüksek güçlü LED'lerin ürün spekleri üzerinden değerlendirme sonuçları verilmiştir. Farklı LED türlerinin yerleşimi ve tasarım konseptleri optik modelleme programlarıyla incelenerek sonuçları sunulmuştur. Sonraki aşamada ise yüksek verimli soğutma sistemi akışkanlar dinamiği programı ile modellenmiştir. Modelleme işlemlerinin ardından optik ve mekanik tasarım parametreleri tespit edilmiştir. Çalışmalar sonrasında öngörülen tasarım zorluklarını aşmak için olası gelecek çalışma konuları da listelenmiştir.

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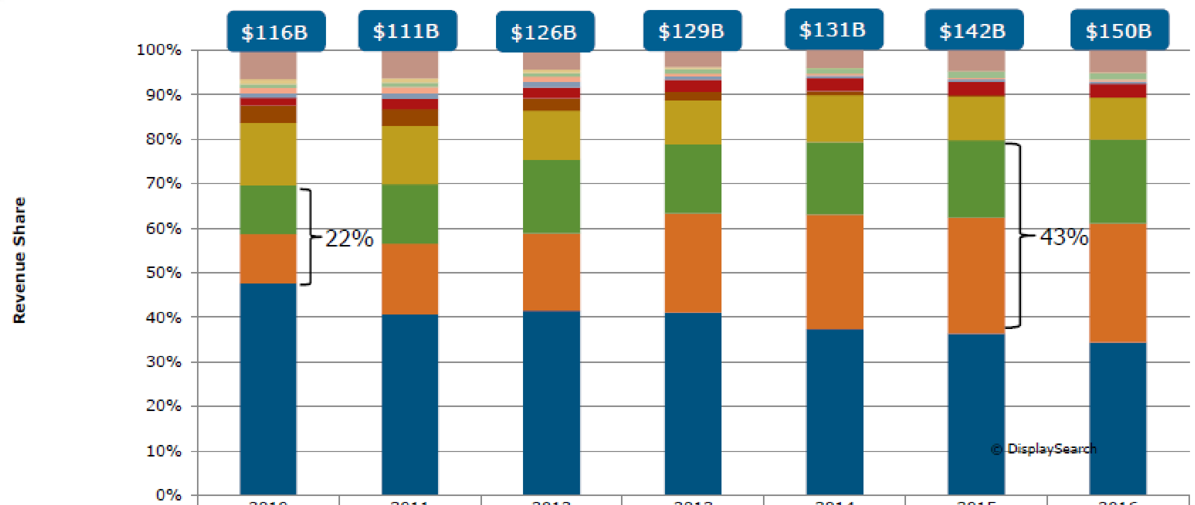
CHAPTER 1

INTRODUCTION

With new technological developments, display devices are taking a very big part in human life. As seen in Display Search research data [1] in Figure 1, total display market revenue is $131 billion in 2014. And 37.4% of this revenue is created by LCD (Liquid Crystal Display) TV market. The main driving forces of this market are cost and technology; therefore, companies are investing on these subjects for development.



	2010	2011	2012	2013	2014	2015	2016
Others	6.6%	6.3%	4.3%	3.8%	3.9%	4.8%	5.1%
Digital Photo Frame	1.0%	1.0%	0.8%	0.4%	0.1%	0.0%	0.0%
Public Display	0.8%	0.9%	0.9%	1.1%	1.2%	1.4%	1.5%
Digital Still Camera	1.3%	1.4%	1.1%	0.6%	0.4%	0.4%	0.4%
Amusement	1.0%	1.3%	1.2%	0.8%	0.6%	0.6%	0.5%
Automobile Monitor	1.7%	2.3%	2.5%	2.7%	2.9%	3.0%	3.1%
Plasma TV	4.0%	3.8%	2.7%	1.9%	0.9%	0.3%	0.1%
Desktop Monitor	14.0%	13.1%	11.1%	9.9%	10.6%	9.9%	9.4%
Mobile PC	10.9%	13.5%	16.4%	15.5%	16.2%	17.4%	18.8%
Mobile Phone	11.1%	15.8%	17.4%	22.4%	25.7%	26.0%	26.8%
LCD TV	47.6%	40.6%	41.5%	41.0%	37.4%	36.3%	34.3%

Figure 1: Display market revenue share in years

After achieving high lumen output levels with recent LEDs (Light Emitting Diodes), these LED’s were started to be used in LCD TV backlighting in 2009. These kinds of LCD TVs became known as LED TVs. LED TVs offer low energy consumption, long lifetime, better-controlled color quality and slimmer design without harmful substances. Due to these advantages, LED TVs have rapidly replaced the conventional CCFL-based (Cold Cathode Fluorescent Lamp) LCD backlight units. The replacement is accelerated by the energy regulations which are put into action by the countries from all over the world in order to take precaution for global warming. Power consumption of the CCFL based LCD TV cannot achieve well levels; therefore they phased out very fast.

There are light emitting pixels (i.e., picture elements) on a display device in order to create the image. Liquid crystal display pixels are not self-emitting therefore they need a uniform light source at the back of pixels. This uniform light source is called the backlight unit (BLU). The cross-section and perspective view of BLU and LC system can be seen in Figure 2. Backlight units have white light therefore white light should be divided into three main colors to create a colored image. LCD TV pixels have three sub pixels which include red, green and blue color filters (CF) to create main colors from white light. The cross-sectional sketch of a sub pixel can be seen in Figure 3.

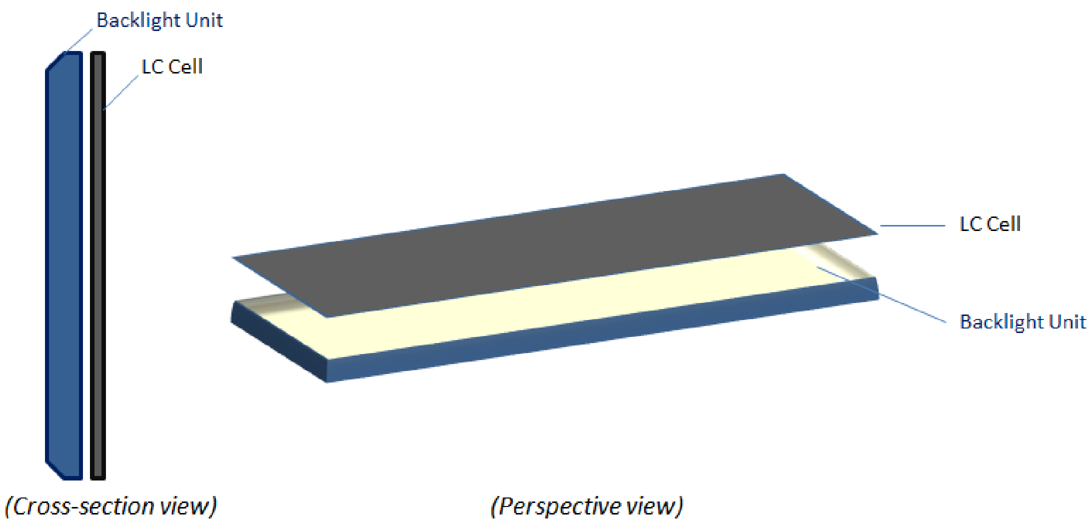


Figure 2: BLU-LC system cross-section and perspective view

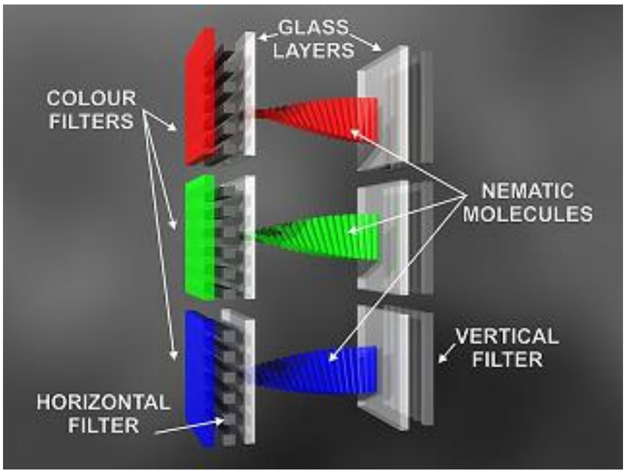


Figure 3: Cross-sectional sketch of a sub pixel structure of an LCD pixel. [2]

LED backlight unit is following Liquid Crystal Cell as the second largest cost adder of a typical LED TV. Therefore, in order to reduce the cost of a TV system for better market competitiveness, optical structure of the backlight unit is one of the best targets. With the help of LED's fast efficacy amelioration, the number of LEDs inside the optical structure can be reduced for lower component cost. To be able to decrease the number of LEDs, some critical design items are listed below.

- High lumen output and high efficacy LED's.
- Improved and optimized Light Guide plate (LGP) pattern design.
- High-gain optical films
- LC cell with high transmittance ratio.
- High performance heat sink design.
- A good optical system design which directs the light for high efficient structure.

In order to reduce the cost and the power consumption of an LED TV, decreasing the luminance is another method in the TV market. Center luminance of the TV's in the market was 400 to 450 nits in 2011 and it decreased to 250 to 300 nit levels in 2012 for entry (low-end) models [1]. The details of the LED TVs' luminance levels can be seen in Table 1.

Table 1: Changes in luminance level for each segments of LCD TV's [3]

		- 2011	**2012 -**
Edge LED	High-End	400 - 450 nit	400 nit
	Mainstream		350 nit
	Entry		250 - 300 nit

Design specifications and technical requirements of small size displays are always lower than big size TV's. Therefore new design structures are realized in small sizes first. In order to foresee large size LED TV design structure, it is the best way to have a closer look at current small size LCD designs in the market. In a backlight unit LED placement trends of big size and small size LED displays can be seen in the Table 2 and Table 3. When the design trends are analyzed, it can be foreseen that next step for the LED TV's is corner-lit backlight units.

Table 2: LED placement trend for the big size LCD's [3]

		2011	2012	2013
Edge	32″ HD 60Hz			
	46″ FHD 120Hz			
	55″ FHD 240Hz			
	Pkg	5630/6030	7030	

Table 3: LED placement trend for the small size LCD's [3]

		2010	2011	2012-
Mobile PC	15.x" N-PC			
	Pkg	208/3810/3014		8015
	9.7" Tablet			
	Pkg		208/3810	

1.1 Motivation and Objectives of the Current Research

After understanding the technology trends of LED TV's, a 32" corner-lit LED TV design is chosen as the primary test vehicle for this study. There are many optical and thermal obstacles for such a TV structure. Optically, optical film structure, light guide plate (LGP) pattern design, lumen output of the LED's and their efficacy have great importance in achieving LED TV's luminance target. Designing LGP pattern to achieve uniform light distribution for the corner-lit system is not easy. Critical optical parameters should be defined for LED and LGP placements and dimensions to be able to increase the light distribution. Total BLU system should have a high efficiency (>10%) to decrease the heat generation and to increase the light output. In order to achieve high lumen output with the limited number of LEDs placed at the corner, it is essential to use high power LEDs. However, in a closed TV structure populated with many heat generating electronics, cooling system must be very efficient to be able to keep the critical optical components of the system at safe temperature levels.

The primary goal of this work is to find out appropriate optical and thermal design metrics and components to develop a novel corner-lit SMART LED TV. The main objectives of this work are summarized as;

- Develop optical models for the TV system and identify design metrics and critical system segments for reducing optical non-uniformity, Mura effect and low optical efficiency.
- Develop a methodology and evaluate possible optical film structures to create an efficient optical sheet design for LED backlight.
- Evaluating possible liquid crystal cell structures in optical domain to obtain efficient optical properties on the TV and understanding their design metrics.
- Studying and down-selecting commercially available power LED products, which are candidates to use corner-lit LED TV, in the market.
- Determining the optical design parameters for LED placement in the backlight unit.
- Determine the thermal implications of corner-lit design system.
- Develop thermal models and develop a cooling strategy to keep the temperature level less than 85 °C for a reliable product.
- Capture novel opto-thermal design ideas and patent appropriate ones for advanced TV system

1.2 Lighting Fundamentals

Visible light is an electromagnetic wave which can be perceived by human eye. The visible light covers the electromagnetic spectrum from 380 nm to 780 nm. The placement of visible light in electromagnetic spectrum can be seen in Figure 4.

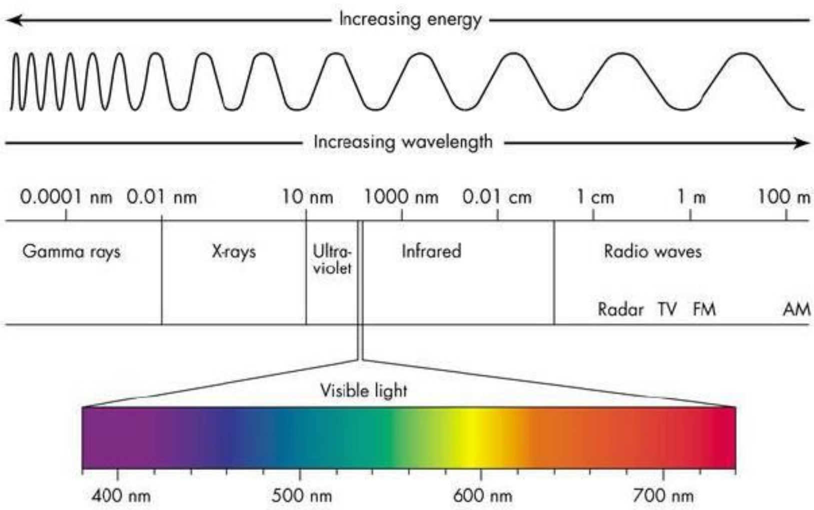


Figure 4: Visible light in electromagnetic spectrum [4]

Color is the response of three different kinds of receptors the human eye to the visible light. Each kind of receptors covers different parts of the visible spectrum. The spectral responses of the receptors can be seen in Figure 5. Color measurement systems define color with hue, saturation and luminance parameters. Munsell and Ostwald defined the system in subjective ways; on the other hand International Commission on Illumination (CIE) defined a quantified system [4].

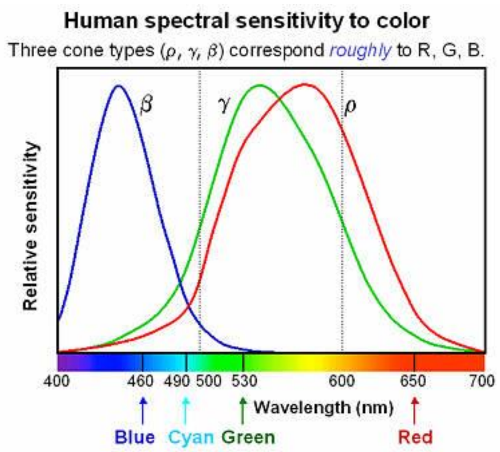


Figure 5: Spectral responses of human eye receptors [4]

CIE 1931 color space is defined with three, namely, X, Y and Z tristimulus spectral functions in order to create a quantified system. After finalizing the study, it was realized that the system can be converted into two dimensional coordinate systems. Two dimensional CIE 1931 coordinate system can be seen in Figure 6. Tristimulus functions can be converted to the x and y coordinates by using the equations below. CIE 1931 is the color space used for display color optical analysis.

$$CIEx = \frac{X}{X+Y+Z} \tag{1}$$

$$CIEy = \frac{Y}{X+Y+Z} \tag{2}$$

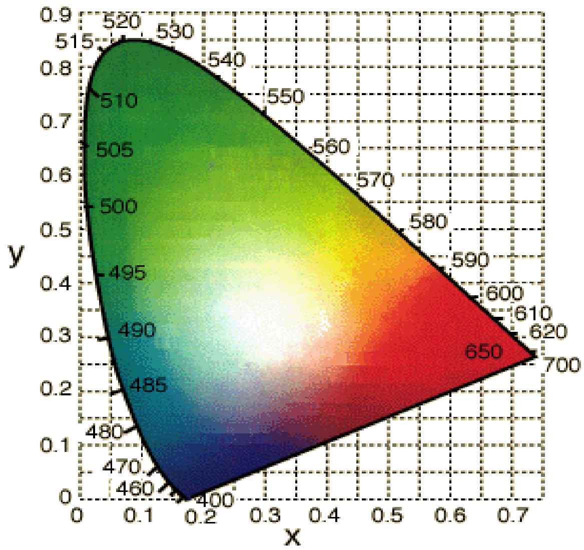


Figure 6: CIE 1931 2D color space [5]

Photometric measure of the intensity of light emitted from a surface per unit area in a given direction is called luminance. The sensitivity of human eye changes with respect to the wavelength of light. As can be seen in Figure 7, human eye is the most sensitive to 550 nm light. This means that, while all electromagnetic waves are at the same level of energy, human eye perceives green area brighter than others. [6][7]

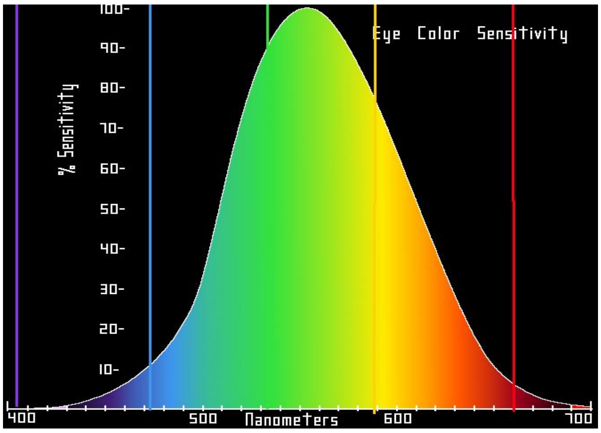


Figure 7: Graph of human eye luminance sensitivity over visible spectrum [8]

LED is a semiconductor device that emits light in narrow band spectrum, structured as a p-n junction. They are used as a light source in LED TV's (LED backlighted LCD TV's). There are various ways to generate white light using LED's which emit almost monochrome light. One basic structure is to use three main colors, namely, red, green and blue LED chips in a single package or multiple packages. Another way is to use ultra violet LED chips and red, green, blue phosphor in the package. The most efficient way is to use blue LED chips and yellow phosphor coating on top, dispense or remote phosphor under the lens. This is the most widely used white light technique in LED TV backlighting due to their high level of efficacy. The inner structure of the white LED and its picture can be seen in Figure 8. The spectral distribution of an LED with blue chip and yellow phosphor can be seen in Figure 9.

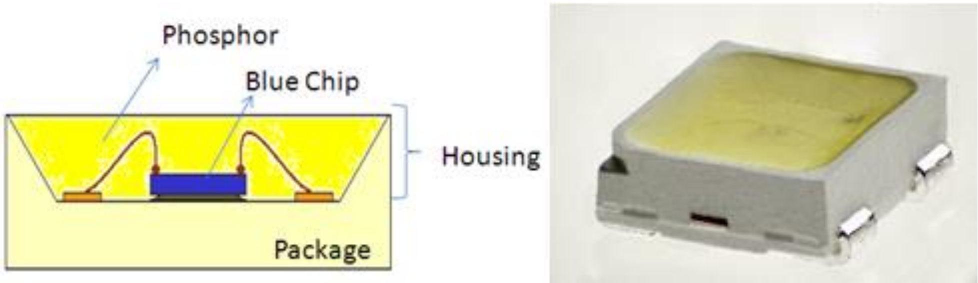


Figure 8: Blue chip and yellow phosphor structure of an LED and its picture [9]

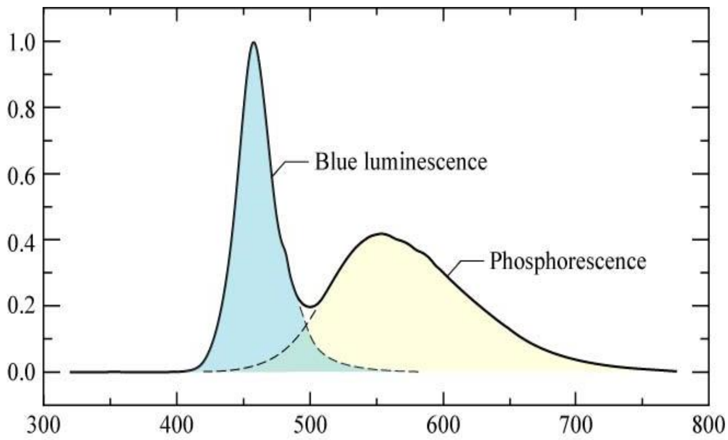


Figure 9: Spectral distribution of a white LED package [10]

1.3 LCD TV Optical Performance Measurements

Major optical performance metrics of an LCD TV are listed in Table 4. LCD panel specification documents should include these performance results. According to the market trends and panel specifications acquired from Vestel Electronics Corp., target TV specifications are defined as indicated in the same table.

Table 4: LED TV target optical specifications

	Target	**Unit**
Contrast Ratio	LC cell spec	-
Response Time	LC cell spec	ms
Center Luminance of White	250	nit
White Brightness Uniformity	75	%
Color Chromaticity	9300	K
Color Gamut	68	% NTSC
Viewing angle	LC cell spec	°

The items indicated as "*LC cell specifications*" as a target, do not depend on the BLU, therefore they are out of scope for this study. Only the BLU-dependent parameters are studied. As stated before, center luminance of white depends on lumen output of LED's, LC cell transmittance and optical design (optical film structure, LGP pattern design) of the backlight unit. White brightness uniformity is defined by LGP pattern's design. Color chromaticity and color gamut are defined by LC color filters and spectral distribution of LED's.

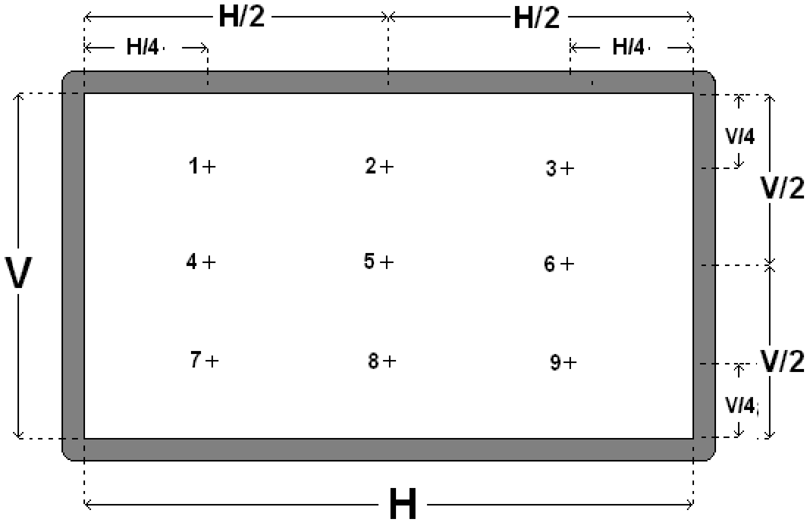


Figure 10: 1/4 uniformity measurement points [Point are determined by the examination of specifications of panels which are located in Vestel Elektronik A.Ş.]

1.3.1 Contrast Ratio (CR)

Contrast ratio is the ratio between the levels of maximum gray (white) and minimum gray (black) at the 5th (center) measurement point. Measurement points can be seen in Figure 10.

$$\boldsymbol{CR} = \frac{Gmax}{Gmin} \quad (3)$$

Where G-max is the brightness when all pixels are white. (Full white), and G-min is the brightness when all pixels are black. (Full black)

Contrast Ratio is a value that depends on the characteristic of the LC cell used in the LCD panel. The ratio changes depending on the light leakage from the backlight when all the pixels of LC cell are closed (full black). This value is dependent on the quality of the polarizers attached on front and back surfaces of the LC cell and the design of the TFT structure.

1.3.2 Response Time

Response time is sum of the transition time from 10% gray level to 90% gray level (T_r) and the transition time from 90% gray level to 10% gray level (T_f). The graphical representation of the response time can be seen in Figure 11.

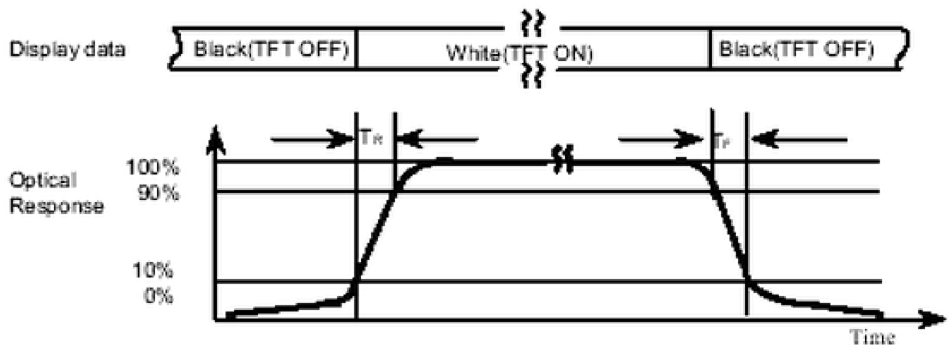


Figure 11: LC cell response time graph [11]

Response Time depends on the response of the LC molecules used in the LC cell to the electric field. This value is affected by the ambient temperature, intensity of the electric field applied at the TFT, viscosity of the LC etc.

1.3.3 Center Luminance of White

It is the luminance of LCD TV at measurement point 5 which is shown in Figure 10. Luminance of white depends on both LC cell transmittance and backlight unit luminance. Because the luminance sensitivity of human eye is high at green region, LCD TV's spectral distribution at this band is the most affective. This spectral distribution is obtained with the light from the backlight unit (Figure 12) filtered by LC color filters (Figure 13). It is not possible to increase the luminance of white by only increasing the green part of the spectrum because LCD TV's correlated color temperature (CCT) should be also within the spec.

Therefore, the spectral quality of both backlight unit light and LC cell CF play a big role on this item.

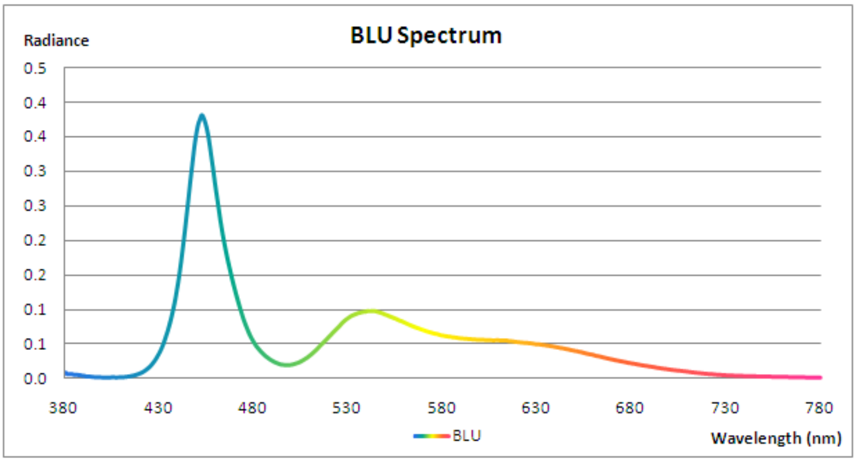


Figure 12: Spectral distribution of an LED BLU

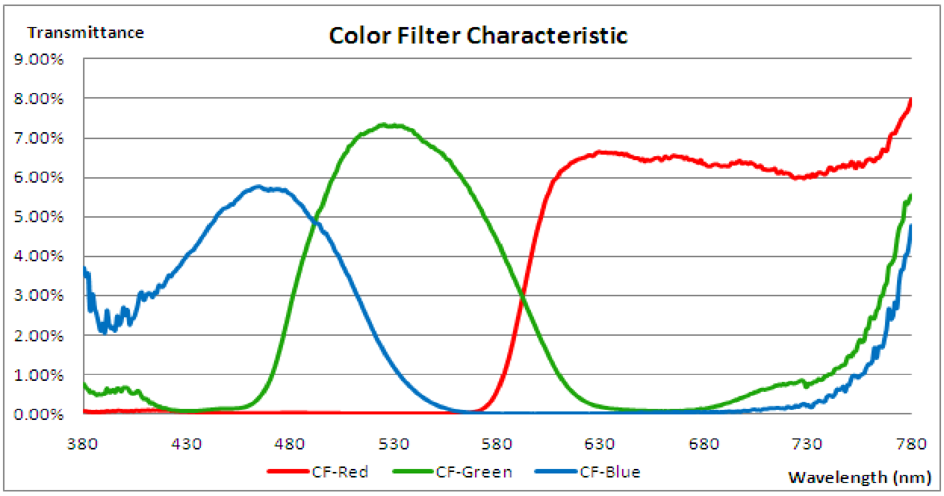


Figure 13: Spectral distribution of CFs of an LC cell

1.3.4 White Brightness Uniformity

It is defined as the ratio between the maximum luminance and the minimum luminance value difference from the 9 measurement points shown in Figure 10. While taking the luminance measurements, the LCD TV should be fed by full white pattern. The calculation formula is given as;

$$\boldsymbol{Buni} = 100 \times \frac{Bmax - Bmin}{Bmax} \tag{4}$$

Where B_{max} is the Maximum luminance of 9 points and B_{min} is the minimum luminance of 9 points. White brightness uniformity is highly dependent on the uniformity of BLU. The quality of BLU light distribution can be improved by a good design of light source and other optical components of BLU.

1.3.5 Color Chromaticity

It is the CIE 1931 color coordinates of LCD TV red, green, blue and white from the center measurement point. Red, green and blue are the colors, which are created with the white light from BLU and filtered by LC as well as cell CFs individually. It can be referred to the Figure 14 – 15 – 16 for the measurement results of red, green and blue color of an LED TV.

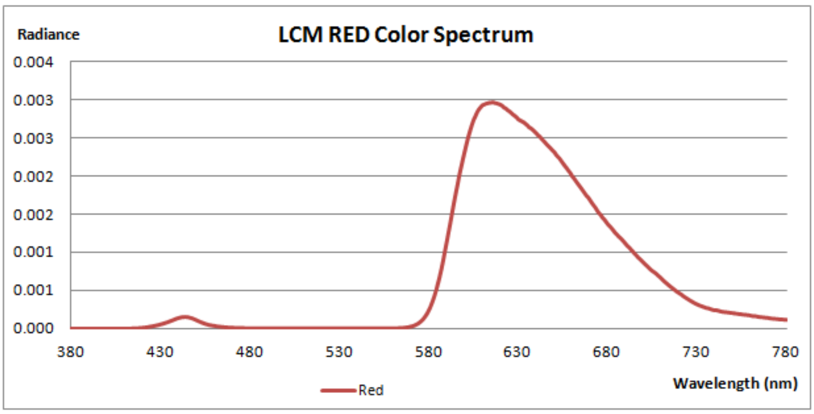


Figure 14: Spectral distribution of red color of an LED TV

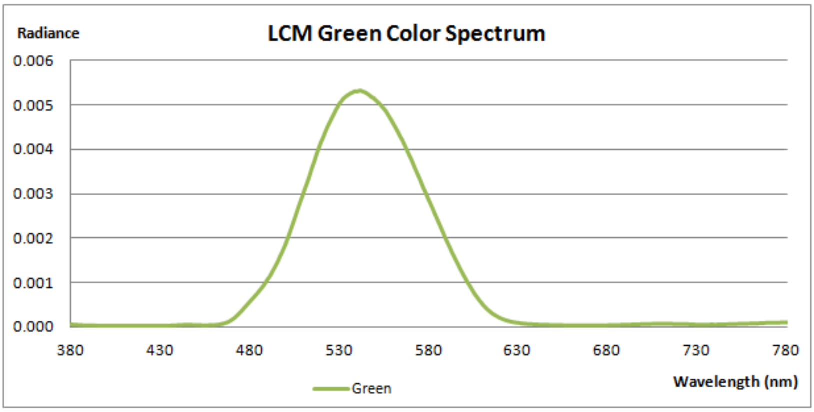


Figure 15: Spectral distribution of green color of an LED TV

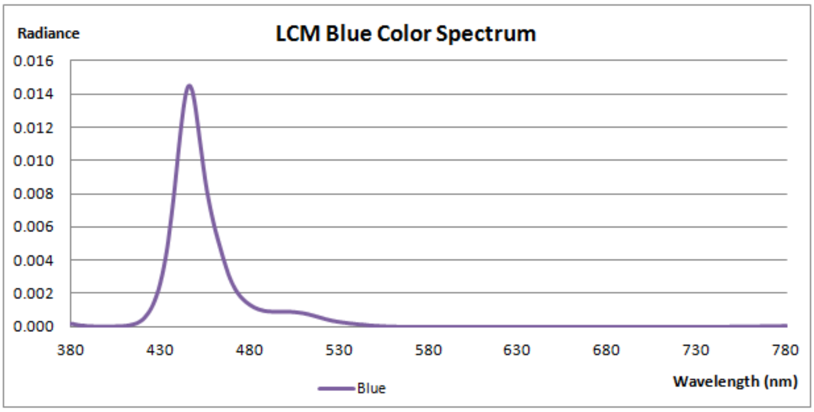


Figure 16: Spectral distribution of blue color of an LED TV

1.3.6 Color Gamut

It is the area of the triangle created in CIE 1931 color coordinate system using red, green and blue colors of the LED TV. This area is commonly compared to the triangle which is defined by NTSC (National Television System Committee) in order to set the quality level of the color gamut. The ratio between them represents the color gamut ratio of TV in NTSC standard. Color gamut of an LED TV and color gamut standard of NTSC can be seen in Figure 17 and Figure 18. High color gamut can be obtained by having pure, narrow spectrum red, green and blue colors of TV. In order to create high quality colors on a white LED back-lighted LED TV, three main colors should be approached to monochrome spectrum by spectral suppression of color filters. . This type of color filter can increase the color gamut; on the other hand, it will decrease the transmittance and the luminance of white. Therefore, while defining the color filter, color gamut and transmittance features should be balanced.

Commonly used color gamut reference is created by NTSC that was established in 1940 to regulate the technical parameters of analog TV's. The color gamut standard was defined for CRT (Cathode Ray Tube) TV's and it is still used for LED TV's. [12]

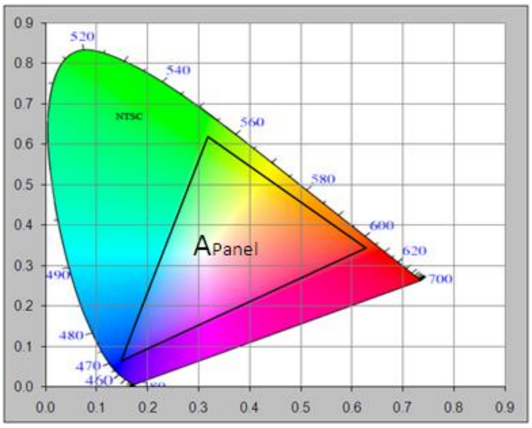


Figure 17: Color gamut of an LED TV

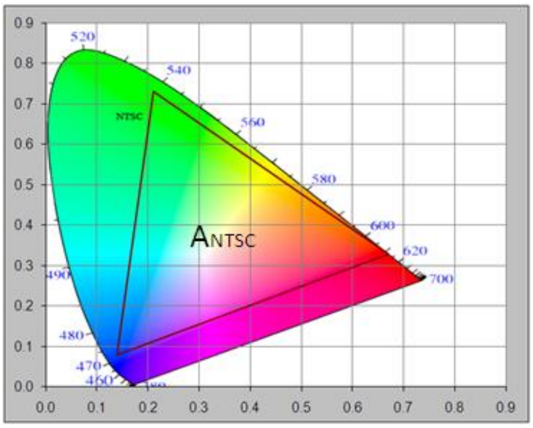


Figure 18 TV Color gamut standard of NTSC

1.3.7 Viewing Angle

For viewing angle definition of an LCD TV, contrast ratio measurements are taken from different angles starting from 0° up to 90°. The angle where contrast ratio drops to 10:1 is the viewing angle of that TV. The measurement setup can be seen in Figure 19.

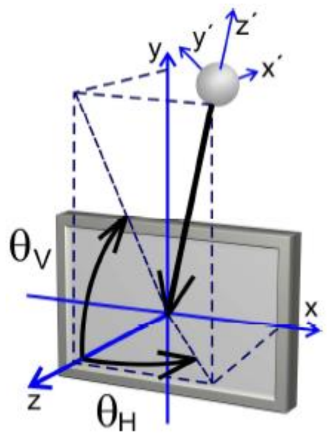


Figure 19: Viewing angle measurement setup [13]

Viewing angle of the TV depends on the LC cell. TFT structure, liquid crystal molecules and angular performance of the polarizer affect this feature.

1.4 Definition of Backlight Unit Specifications

After definition of TV luminance targets and decision of the LC cell, optical targets of the backlight unit can be calculated. If there is no reflector polarizer in the optical film structure and the spectrum of the target BLU is almost the same as the BLU which is used for LC cell characterization measurements, BLU luminance target can be calculated by dividing the TV luminance target to the LC cell transmittance ratio. Reflective polarizer is an optical film which transmits the one linear polarization that can pass through the bottom absorptive polarizer of LC cell and reflects back the other polarization perpendicular to bottom polarization of LC, into the backlight unit and prevents almost 30% light loss. Details of the reflective polarizer will be explained in the next chapter. The effect of light source spectrum is also important for the calculation of the luminance target of the backlight. The transmittance ratio of the LC cell is defined by evaluating the individual responses of its color filters to the spectrum of the BLU light source. If the spectrum changes, the transmittance response will also be changed.

1.5 BLU Optical Films

LED TV backlight unit optical structure contains the PCB contains LEDs on top (LED bar), optical films and light guide plate (LGP). A standard LED TV backlight unit structure can be seen in Figure 20. Before the definition of the backlight unit optical structure, LED's in the market are investigated for a good technical and commercial solution. After the definition of the optical structure, optical film structure is defined according to the target backlight unit optical specs. In this study high power LED's are used, therefore possible thermal problems, due to high power, should be considered. For that purpose, in the first step, optical structure which has the highest gain is determined in order to decrease the heat dissipation of the LED's.

The main purpose of the optical film structure is suppressing the luminance discontinuities, increasing the luminance in the perpendicular direction and increasing the LC cell efficiency by decreasing the absorption in the first polarizer layer (analyzer). Features and functions of the optical films are explained in the part below.

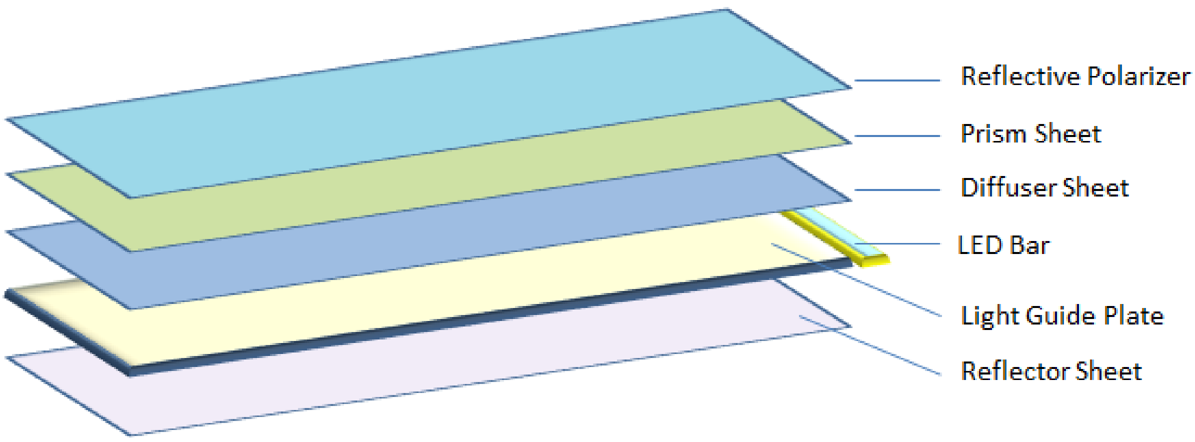


Figure 20: Backlight unit optical structure.

1.5.1 Reflector Sheet

Reflector Sheet is placed at the backside of the BLU optical film structure, on top of metal back chassis. The main purpose of reflector sheets is to redirect the light propagating away from the active screen. The most important features of the reflector sheets are high reflectance ratio, small color difference between incident and reflected light (color shift) and high diffusion. Higher reflection means higher optical efficiency for reflector sheets. In order not to have a big color shift, reflectance of the product across whole visible spectrum should be almost constant. In the backlight industry, reflector sheets are made out of white-PET (Polyethylene terephthalate) material and the reflection is provided by the voids inside the sheet. Due to the reflective index difference between void and PET, incident light reflects from the sheet. Typical reflectance of the sheets in the market is around 96~98%. The cross sectional sketch of a reflector sheet can be seen in Figure 21. The top surface of the reflector sheet is rough in order to prevent the electrostatic discharge (ESD) and scratches while assembling the LGP on top of the reflector sheet.

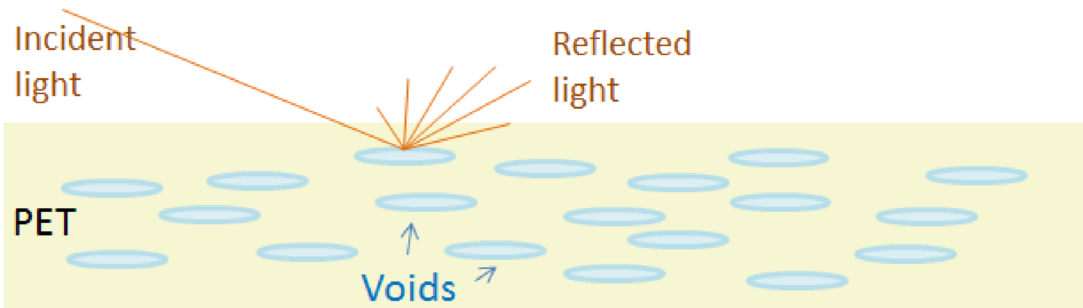


Figure 21 Cross sectional sketch of a reflector sheet

1.5.2 Light Guide Plate (LGP)

LGP is the essential component of the LED TV’s. The purpose of the LGP is to diffract the directional LED light towards the active screen in a uniform manner. PMMA (Poly-methyl methacrylate) material, which is optically high efficient and durable, is mainly used to produce the LGP's. Various production methods, such as ink printing, laser, v-cut or molding, are used to obtain LGP patterns. Working principle of LGP is shown in Figure 22.

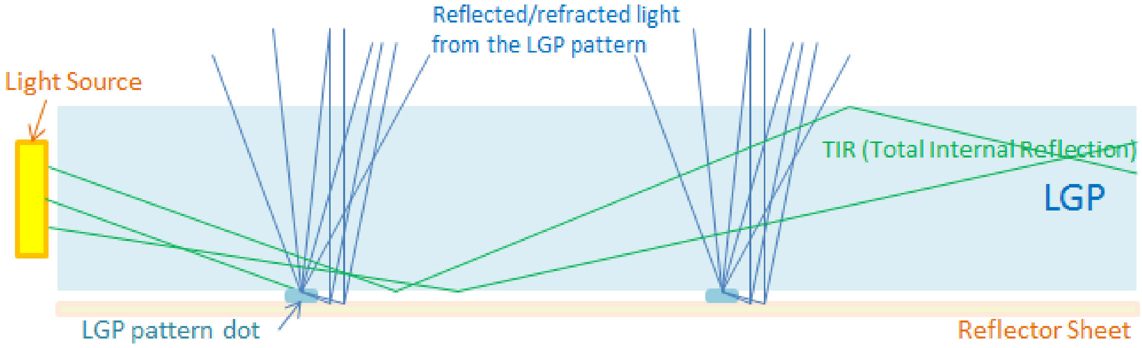


Figure 22: Working principle of the LGP

1.5.3 Diffuser Sheet

The main purpose of diffuser sheets is to decrease the discontinuities of light distribution on the screen. They function like a low-pass light filter within the backlight units. They can hide both hot spots of luminance peaks and some of the defects, which are caused by other components of the backlight unit. Substrate material of diffuser sheets is transparent PET. Diffuser sheets are coated by acrylic beads with a resin. There is a lower concentration of beads at the bottom of the substrate in order to prevent ESD with other sheets [14]. Cross-sectional sketch of the diffuser sheet can be seen in Figure 23. Due to their shapes, acrylic beads can also collimate the light towards the viewer direction axis.

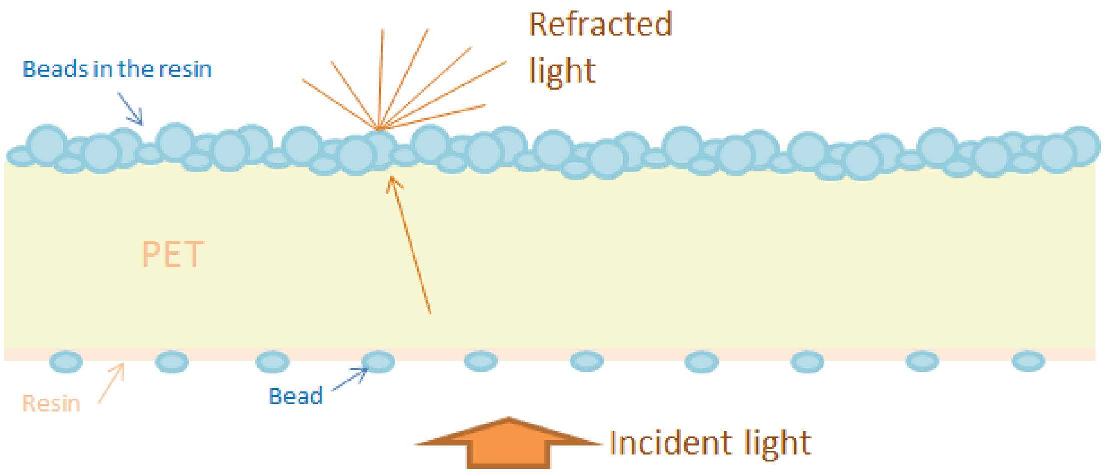


Figure 23: Cross-section sketch of diffuser sheet

1.5.4 Prism Sheet

As the name implies, Prism Sheets consist of a prismatic structure located on top of a transparent PET substrate. The only purpose of this sheet is to collimate the light on to the axis of the display via its prismatic structure. The working principle and cross sectional sketch of prism sheet can be seen in Figure 24. There are horizontal and vertical prismatic structure types. According to TV luminance target, both types can be incorporated in the same structure. The disadvantage of this sheet is the dramatic reduction of the luminance at wide viewing angles. The prism angle is usually 90º on the top in order to obtain the highest gain.

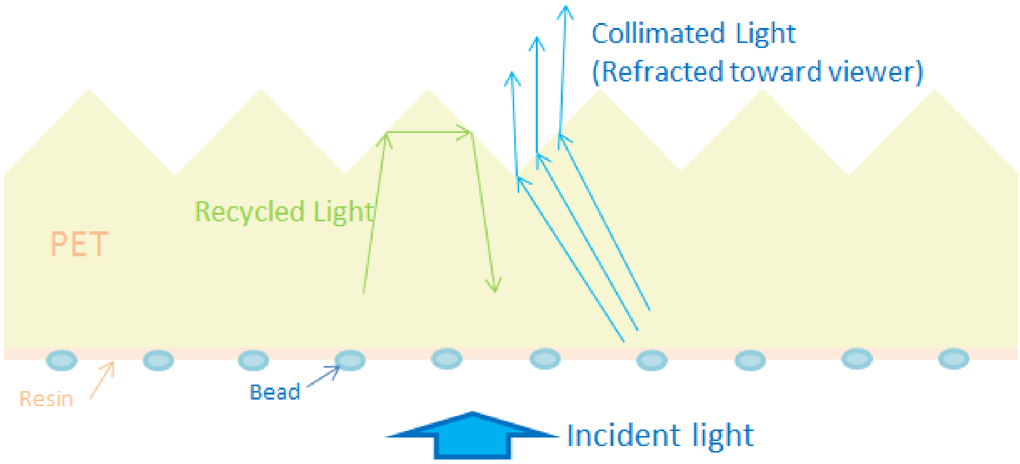


Figure 24: Working mechanism and cross sectional sketch of prism sheet

1.5.5 Reflective Polarizer Film

The bottom polarizer of the LC cell absorbs Fifty percent of the light created by BLU. In order to decrease this loss, reflective polarizer film is used as the top layer of the optical film structure. Light refracts according to its polarization while changing mediums which have different refractive indices. Reflective polarizer film uses this phenomenon to reflect the light which will be absorbed by the absorptive polarizer. It has PET layers in the middle covered by PC layers at the top and bottom surfaces. The reflected light (Shown as P2 in 40) passes through the BLU structure back and forth and some of P2 polarization turns into P1 polarization which can pass through the first polarizer. The working principle of reflective polarizer can be seen in Figure 25. Using this film increases the measured transmittance of the LC cell [15] [16].

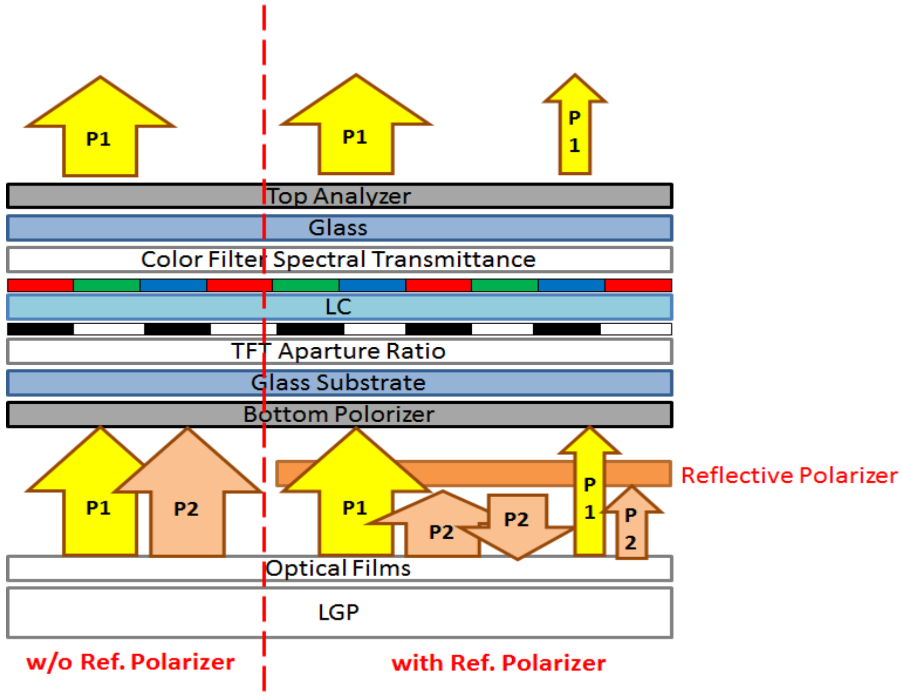


Figure 25: Sketch of working principle of reflective polarizer.

1.6 LCD TV Thermal Performance Measurements

LED's are extremely prone to high temperatures. Lumen output and quality of light, as well as the product lifetime are directly affected by the changes in the junction temperature. Although the advantages of the corner-LED structure are abundant, a very planned thermal study with computational and experimental packages must be performed.

The key aspect of the thermal studies in LED Backlight design studies is the LED Junction temperature. High LED Junction temperatures can lead to degradation of the LGP and optical films, as well to a shortened LED lifetime, which causes a shorter lifetime for the product. Using an aluminum heat sink is the current best practice in the industry for dissipating the heat in order to decrease the LED Junction temperature, where the heat dissipation is based on conduction. [17]

Most of the heat is generated by light source in LCD TV's. Therefore, components, which are located close to LED's, define the thermal specifications of the system. Due to the particle/dust sensitivity of LCD TV's, the inner structure is sealed from the ambient. Therefore conduction is the only way to dissipate the heat. In order to keep a satisfactory reliability level, temperatures of all components should be lower than their respective maximum allowed temperature specifications.

Table **5** shows the critical temperature of the components.

Table 5: Critical temperature level of the components.

	Max. Allowed Temp. (°C)
LED Junction	150
LC Cell surface	65
Optical Films	85
Light Guide Plate	90

CHAPTER 2

OPTICAL EXPERIMENTAL STUDY

An experimental system has been developed to characterize the optical film structure of the BLU and LC cell of the TV. The ambient conditions should be set according to the display measurement standards. Measurements are taken in a windless, dark room (<10 lux) with 25 ± 2 °C ambient temperature. Warm up time should be adequately long until the luminance of LCD becomes stable to conduct the tests. Measurement device (spectro-radiometer) must be placed in front of the panel and directed perpendicularly to the center as can be seen in Figure 26. The distance must be 50 cm from the panel and the focus should be on the surface of the screen during measurements [18].

Figure 26: Optical measurement device setup for LCD TV

All spectral measurements were executed using a TOPCON SR-LEDW spectro-radiometer. This device is one of the widely used measurement device in the display industry. It uses diffraction grating to disperse the different wavelengths. Its wavelength range covers 380 nm to 780 nm visible spectrum. Luminance accuracy is higher than 98%

and its chromaticity accuracy is ±0.002 [19]. The optical measurement setup picture can be seen in Figure 27.

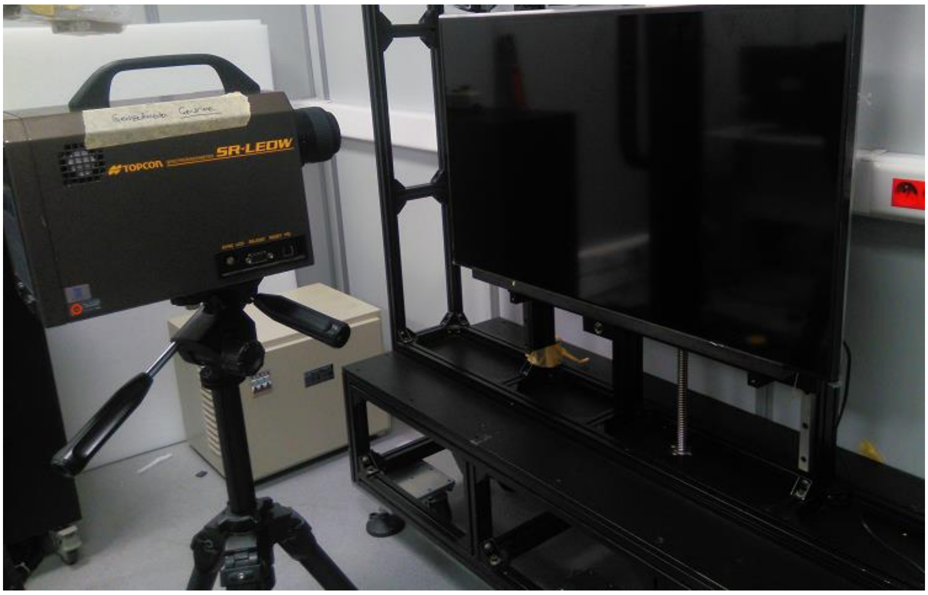


Figure 27: Optical measurement setup. Spectro-radiometer is placed 50 cm away from the panel.

While measuring the LC cells, a standard 32” LED TV backlight was used. In the first step, spectral measurement of LED TV backlight unit was executed to expose the base of the LC cells. In order to analyze the LC cells, LC panels (backlight + LC cell) were fed with full white (R255, G255, B255), full red (R255, G0, B0), full green (R0, G255, B0) and full blue (R0, G0, B255) patterns to obtain the spectral characteristics of individual Color Filters, as described in the above sections.

2.1 LC Cell Evaluation and Analysis

Efficiency of LCD technology is highly dependent on LC cell transmittance. The efficiency of the backlight unit is almost 80 % but the LC cell transmittance is around 5%

to 10%. This value changes according to cell technology (TN, IPS, VA, etc…), size, resolution and CF spectral characteristic of the LC cell. If the size is increased, aperture ratio of TFT array and transmittance also increases. If the resolution is increased, aperture ratio of the TFT array and transmittance decreases. If the color filter spectral transmittance is high, it directly affects the cell transmittance. As indicated before, the most effective CF is green because the human eye luminance perception is highest in this spectral region. Then increasing only the green CF transmittance seems enough. But transmittance is not the only parameter while defining the color filters. Color gamut and correlated color temperature effects of the CF should also be considered. Approximate optical efficiency of LC cell layers can be seen in Figure 28.

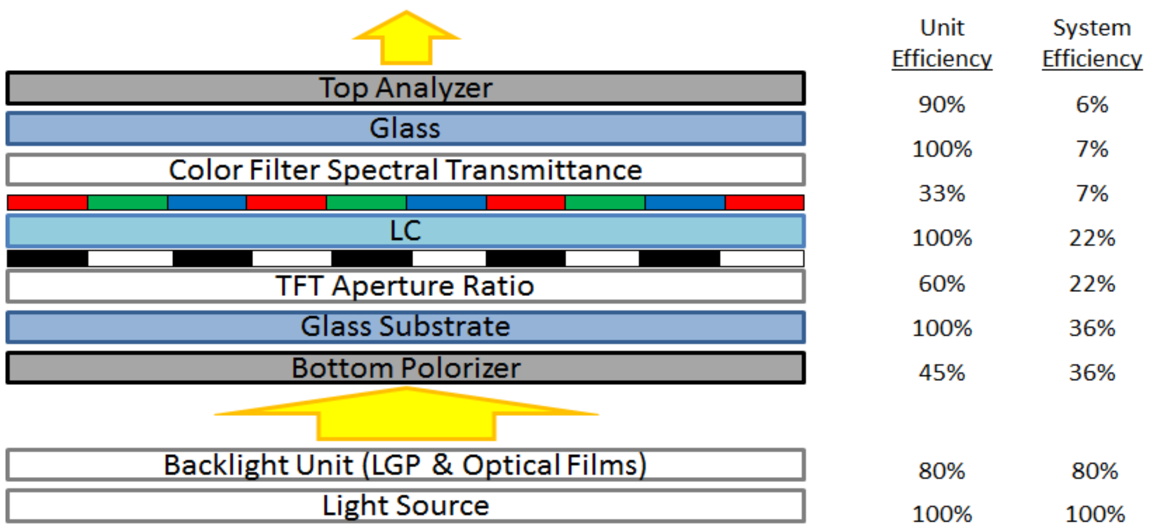


Figure 28: Approximate optical efficiency distribution of LC cell layers

While designing an LED TV backlight unit, the first step is the evaluation of the LC cell optical characteristics to design an efficient optical structure. Therefore, color filter and transmittance of six different 32” LC cell models listed in Table 6 were optically analyzed.

Table 6: List of evaluated LC cell models

#	Producer	Product Name
1	SDC	LTA320AN01
2	BOE	HV320WX2-201
3	AUO	T320XVN01.0
4	AUO	T320XVN02.0
5	CSOT	ST3151A05-1
6	LGD	LC320DXJ-SFE1

Optical measurement results of the standard 32” backlight unit are given in Table 7 and corresponding spectral distribution can be seen in Figure 29. Blue chip and red enriched yellow phosphor white LED’s were used in the backlight unit. The narrow peak at 464 nm seen in Figure 29 is the spectral response of the blue chip. Wide spectral distribution of yellow phosphor has a peak at 548 nm. Additional red phosphor response and its peak are observed around 646 nm wavelength.

Table 7: Standard backlight unit optical measurement results

	Tristimulus			**L (nit)**	**CIE x**	**CIE y**
	X	**Y**	**Z**			
BLU	4354	4054	7100	4054	0.2807	0.2614

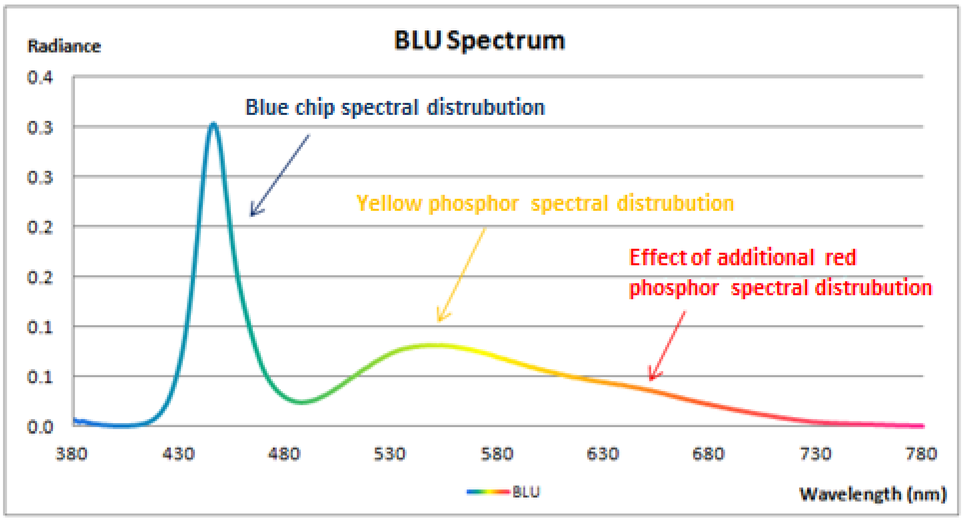


Figure 29: Spectral distribution of the backlight unit

Following the BLU spectral measurements, BLU and Cell spectral measurements were performed with all six LC Cells described in Table 6, After obtaining the white, red, green and blue spectral measurements, using the cells and the standard backlight unit, color filter characteristics were calculated by extracting the LC Cell spectral results from BLU results. Three color filter spectral distributions and respective spectral transmittance ratios of the LC cells can be seen in Figure 30, Figure 31 and Figure 32. The transmittance level of the filters directly affects the luminance of the colors. Green color filters transmission has the biggest effect on the transmittance of the LC cell because the human luminance perception is high in this region.

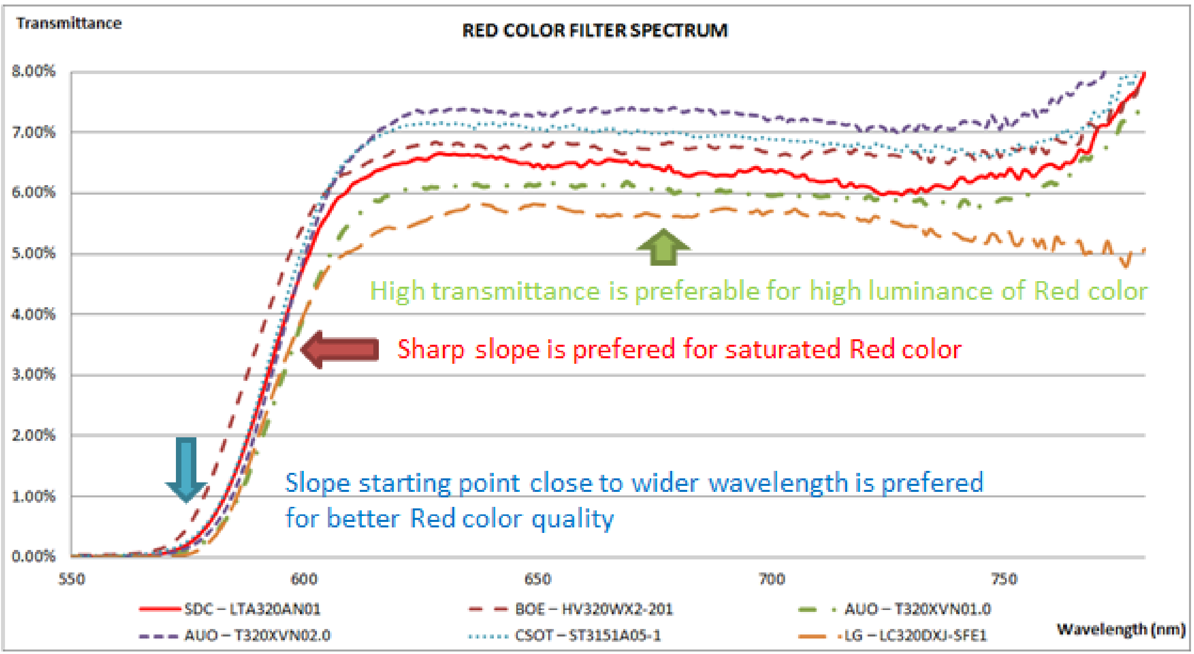


Figure 30: Red Color filter spectrum of the LC cells.

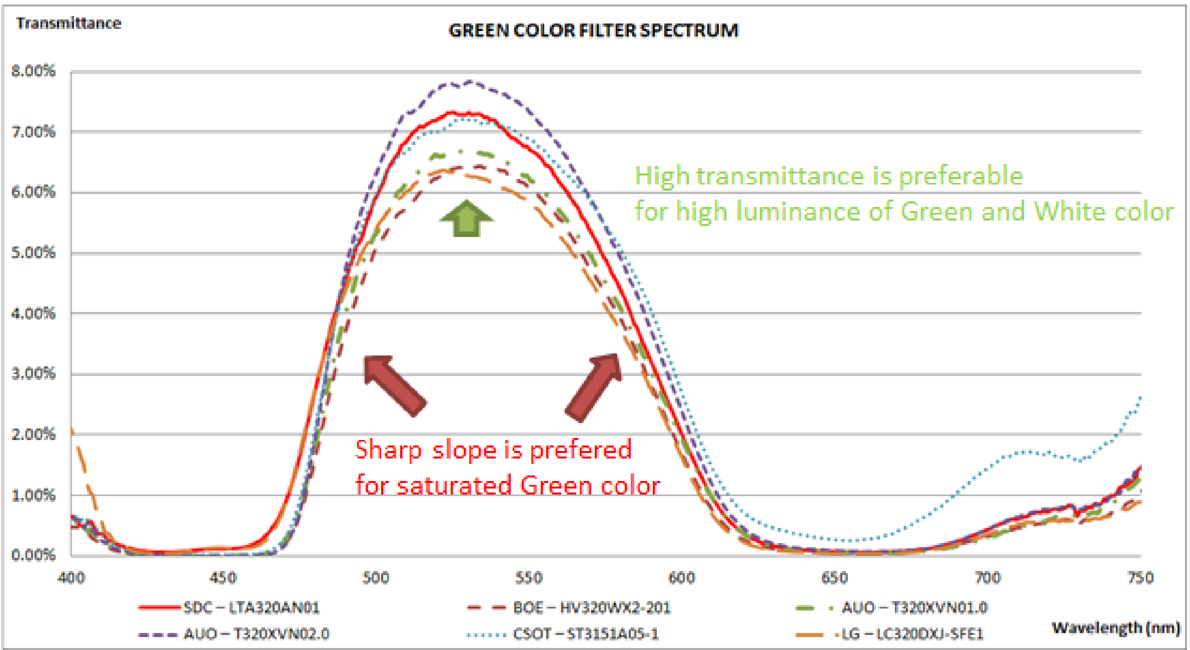


Figure 31: Green color filter spectrum of the LC cells.

Starting points of the slopes of the color filters affect the saturation of three main colors. In other words, they affect the color gamut of the TV. Due to blue chip's narrow bandwidth emission, blue color filter does not affect the color gamut. If the starting point of the slope is expanded to wider wavelengths, the yellow phosphor emission can pass through the blue filter which decreases the saturation of the blue color.

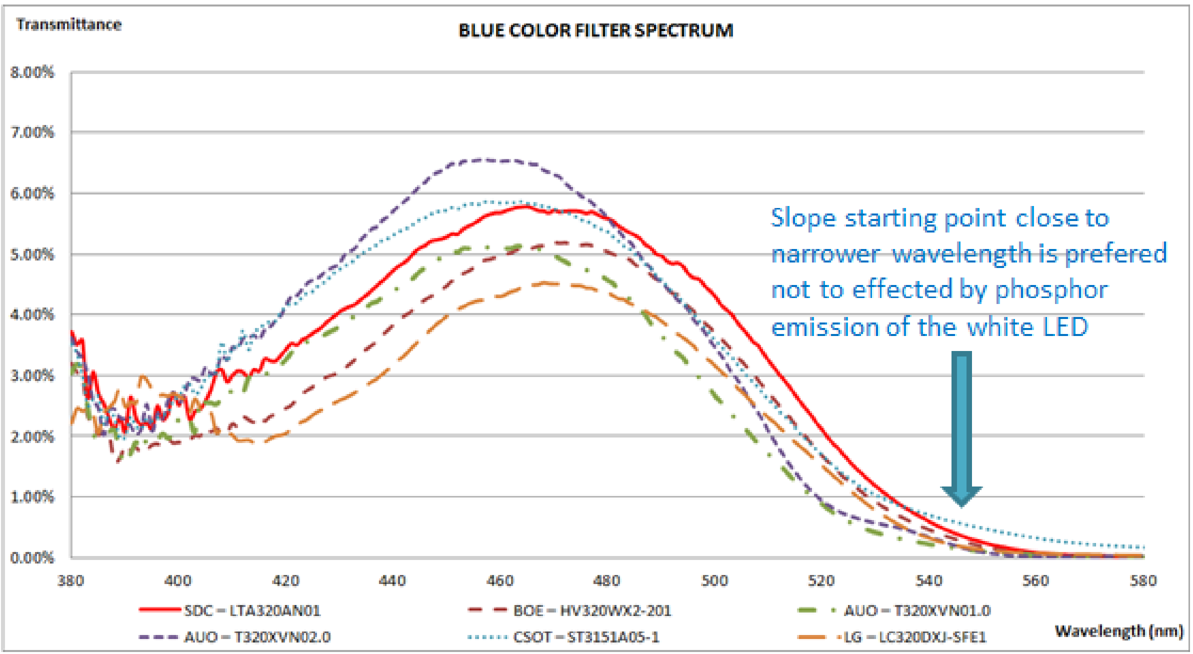


Figure 32: Blue color filter spectrum of the LC cells.

Optical measurement results of the LC panels are listed in Table 8. In order to achieve the optical targets of the LED TV, the critical judgment points for optical values are the luminance and color gamut, the transmittance ratio of the LC cell should be high to obtain the high luminance with low LED lumen output. When the transmittance ratio is taken into consideration, CSOT (7.38%) and AUO v02 (7.24%) have the two highest values. In addition to the luminance, color gamut is also a critical feature of the TV. In terms of color gamut levels, AUO v01 (74.6% NTSC) and AUO v02 (73.7% NTSC) are the best two cells. However, CSOT that has the highest transmittance ratio level in the LC cells, has only 65.2% color gamut of NTSC. This value is below the level of LED TV color gamut target which is 68% NTSC. Therefore, AUO v02 is the suitable LC cell for efficient backlight unit design.

Table 8: Optical measurement results of LC cells

		BLU	Red	Green	Blue	White	Color Gamut NTSC (%)	Cell Tr (%)
SDC	CIE x	0.2584	0.6494	0.3028	0.1477	0.2822	70.9	6.98
	CIE y	0.2305	0.3312	0.5914	0.0610	0.2942		
	L (nit)	4054	45	202	37	283		
BOE	CIE x	0.2700	0.6279	0.3185	0.1485	0.2804	69.2	6.47
	CIE y	0.2422	0.3432	0.6201	0.0650	0.3306		
	L (nit)	4054	55	177	29	262		
AUO v01	CIE x	0.2772	0.6445	0.3224	0.1523	0.2854	74.6	6.08
	CIE y	0.2543	0.3244	0.6215	0.0458	0.2959		
	L (nit)	4054	39	188	20	246		
AUO v02	CIE x	0.2900	0.6467	0.3309	0.1532	0.2633	73.7	7.24
	CIE y	0.2700	0.3264	0.6199	0.0468	0.3040		
	L (nit)	4054	50	220	23	293		
CSOT	CIE x	0.2807	0.6288	0.3369	0.1560	0.2919	65.2	7.38
	CIE y	0.2614	0.3273	0.6053	0.0705	0.2959		
	L (nit)	4054	51	213	36	299		
LGD	CIE x	0.2719	0.6510	0.3048	0.1509	0.2712	71.5	5.84
	CIE y	0.2465	0.3304	0.5990	0.0653	0.3411		
	L (nit)	4054	37	176	24	237		

When the CF spectrums of CSOT and AUO v02 LC cells are examined, the reason of the color gamut difference can be seen. CSOT and AUO v02 LC cell CF spectrum plots are given in Figure 33. Due to the human high luminance sensitivity near green wavelength (550 nm), AUO v02 has the luminance efficiency advantage because of its higher green color filter transmission. The difference is shown with the arrow number 1 in Figure 33. On the other hand, CSOT has higher transmittance ratio at the part shown with arrow number 2 (from 500 nm to 580 nm) of the blue color filters that covers some part of the high luminance sensitivity area of human eye. As a result, their transmittance levels are almost same. Since CSOT CF has high transmittance in region 2, its blue is not as deep (saturated) as that of AUO v02. Moreover, AUO v02 CFs have higher transmittance at the primary color parts of the visible spectrum which are shown with the arrow numbers 1, 5 (430 nm to 480 nm) and 4 (630 nm to 730 nm) in Figure 33. This provides more saturated colors to AUO v02 than CSOT. The region defined with the arrow number 3 shows the reason of poor green color saturation of CSOT cell. The color gamut difference between two LC cells can easily be realized when the color coordinates are examined in CIE 1931 table which is given in Figure 34.

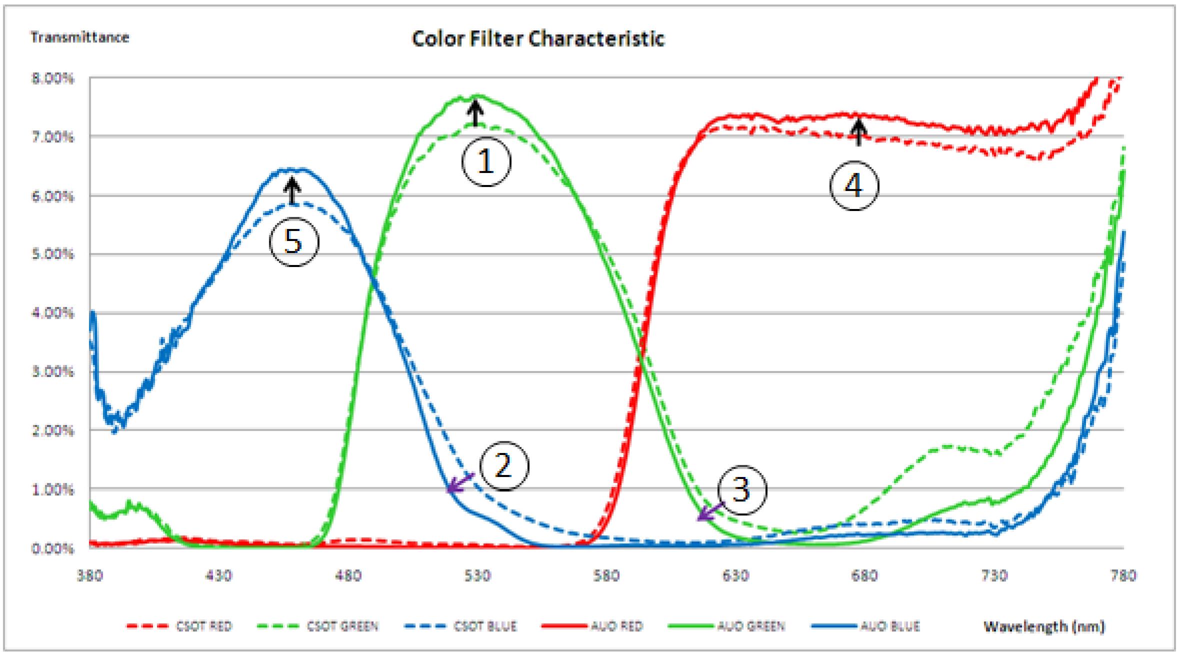


Figure 33: Spectral distribution of CSOT and AUO-v02 LC Cell color filters

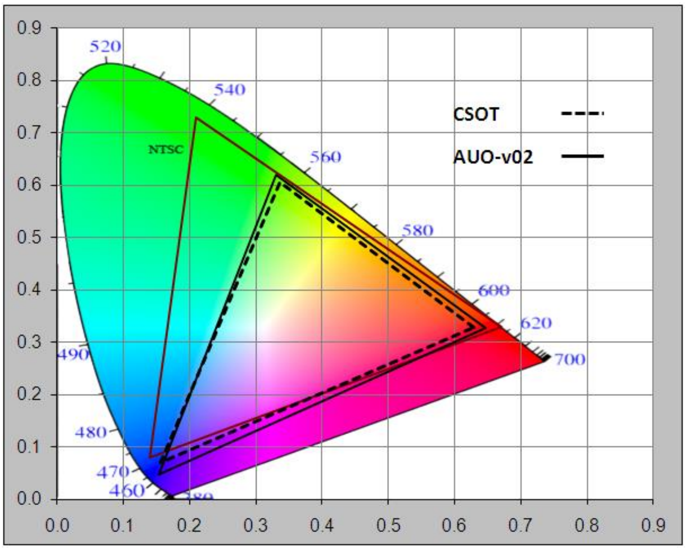


Figure 34: CSOT and AUO v02 LC panels color gamut in CIE 1931 color space

In order to reduce the number of optical measurements for further BLU optical structure studies, a calculation method is developed to obtain TV results with LC color filter data. In this method, the first step is measuring the radiometric spectrum of backlight unit and of WRGB of LC panel (TV). After that, extraction of color filter data of the LC cell is done by using these measurement results. Next step is transformation of radiometric data into photometric data using CIE 1931 XYZ tristimulus values which are represented in formula number 3, 4 and 5. In the last step, luminance and CIE 1931 color coordinates of LC panel are calculated using transformation formulas numbered 6, 7 and 8 [20].

$$X = \int_{380}^{780} I(\lambda)x(\lambda)d\lambda \tag{5}$$

$$Y = \int_{380}^{780} I(\lambda)y(\lambda)d\lambda \tag{6}$$

$$Z = \int_{380}^{780} I(\lambda)z(\lambda)d\lambda \tag{7}$$

$$L = Y \quad (8)$$

$$\text{CIE } x = \frac{X}{X+Y+Z} \quad (9)$$

$$\text{CIE } y = \frac{Y}{X+Y+Z} \quad (10)$$

With this calculation method, optical measurement results of any BLU and LC cell combination can be obtained by only implementing the related spectral data sections of the system. The flow chart of the method can be seen in Figure 35.

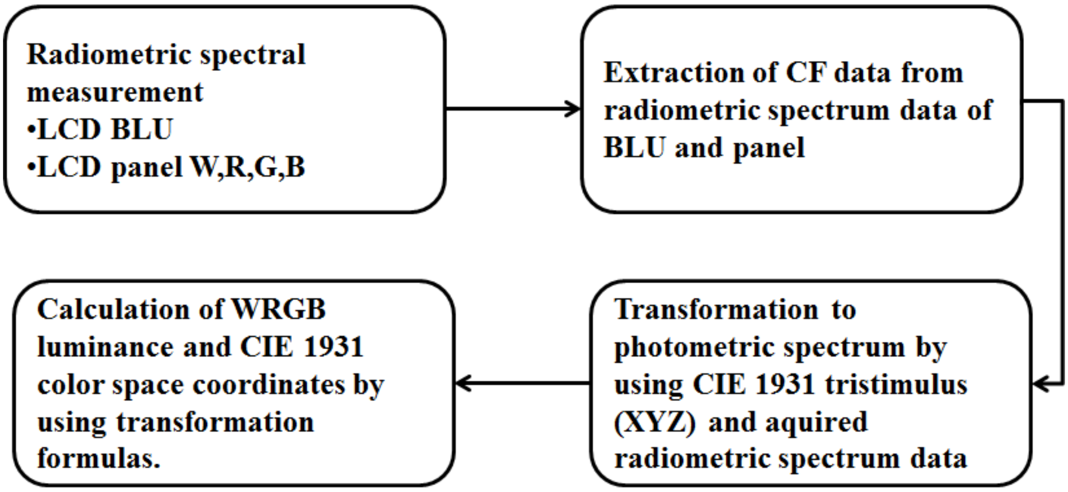


Figure 35: Flow chart of calculation method of LC panel optical measurement results

In this study, LED's will be the light sources therefore transmittance ratio will be considered to be the same as calculated in previous section. The luminance target calculation of BLU is done by using formula (9) and the result is obtained as 3453 nits.

$$\text{BLU L.} = \frac{\text{Target TV L}}{\text{LC Cell Transmittance}} = \frac{250}{0.0724} = 3453 \text{ nit} \quad (11)$$

While defining the BLU CIE 1931 color coordinate targets, the color coordinate difference between TV white pattern and BLU is taken as a reference. Correlated color temperature (CCT) target of the LED TV is 9300K. There is a color coordinate representation of Planckian (black body) locus in CIE 1931 system. The black body locus in CIE 1931 color system can be seen in Figure 36. The TV target 9300 K corresponds to (0.285, 0.293) CIE 1931 color coordinates. Therefore, the color coordinate difference between BLU to TV called LC cell color shift is extracted from the TV target, in order to calculate the CIE color coordinate targets of the BLU. Formulas number 10 and 11 can be checked for TV BLU CIE coordinates calculations with their references. The formula and the calculation of can be seen below. The calculation inputs and results are given in Table 9.

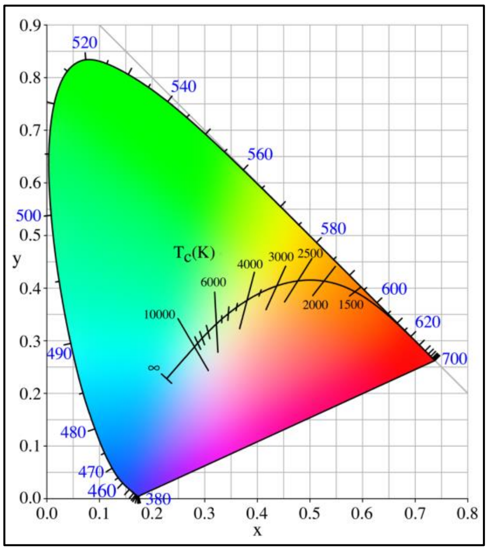


Figure 36: Planckian locus representation in CIE 1931 coordinate system

$$\textbf{BLU CIEx} = \text{Target\_CIEx} - \text{LC\_CIEx\_Shift} = 0.285 - 0.0018 = 0.2832 \qquad (12)$$

$$\textbf{BLU CIEy} = \text{Target\_CIEy} - \text{LC\_CIEy\_Shift} = 0.293 - 0.0345 = 0.2585 \qquad (13)$$

Table 9: Backlight unit optical spec calculation results

Input						Output		
Target L. (nit)	Target CIE-x	Target CIE-y	LC Trans.	CIE-x Shift	CIE-y Shift	BLU L. (nit)	BLU CIE-x	BLU CIE-y
250	0.2850	0.2930	7.24%	0.0018	0.0345	3453	0.2832	0.2585

2.2 Optical Film Structure

While defining the optical film structure, luminance gain of various optical film combinations are measured. All measurements are performed in conditions of LED TV measurements defined in previous sections. A standard 32” LED TV’s backlight unit is used to conduct the tests. After defining the luminance gain of the sheet structures, the LED lumen outputs required to achieve the luminance target for each structure are also calculated.

Five different optical film structures are evaluated in order to choose the most efficient structure. The backlight unit used in the study has 3 diffuser sheets as the optical film structure, 2304 lm lumen output from the LED’s and it is calculated using the previously presented formulas that the structure provides 320 nits luminance at the center of the TV. In our system TV luminance target is 250 nits therefore LED driving current is decreased as the first step. Then, the luminance gain of the structure is increased by using prism and reflective polarizer sheets. The increment is performed step by step. According to the results presented in

Table **10**, the film structure including one horizontal prism sheet, one vertical prism sheet and a reflective polarizer has the maximum luminance gain. When three diffuser sheets structure is taken as a reference, two prisms and reflective structure has 2.24 times higher luminance result. With this structure, the required lumen output of the LED’s is decreased to 812 lm.

Table 10: Measurement results of different optical film structures

	Input	Design #1	Design #2	Design #3	Design #4	Design #5
Reflector sheet	W.PET	W.PET	W.PET	W.PET	W.PET	W.PET
Optical film #1	DS	DS	DS	DS	PS	PS
Optical film #2	DS	DS	MLF	PS	PS	PS
Optical film #3	DS	DS	DS	DS	DS	RP
LGP uniformity	75%	75%	75%	75%	75%	75%
Optical film gain	100%	100%	111%	127%	140%	224%
Panel Lum. (nit)	320	250	250	250	250	250
LED Bar L.flux (lm)	2304	1806	1632	1409	1294	812

W.PET : White PET reflector sheet.

DS : Diffuser Sheet

MLF : Microlens Sheet (ordered bead diffuser)

PS : Prism Sheet

RP : Reflective Polarizer Film

2.3 LED Chip/Package

After determining the LC cell and optical film structures, next step is to choose LED chip and package according to the target luminous flux. According to the measurement results presented above, the required lumen output of the LED's was determined as 812 lm.

In TV market, 7020 (7.0 mm x 2.0 mm) and 7030 (7.0 mm x 3.0 mm) LED packages are the most common packages. According to their specifications, the maximum driving current is around 180 mA while they have 2 serial chips inside leading to a maximum luminous flux of 120 lm at 180mA per package. In order to achieve 812 lm with these LED packages, at least 8 of them should be used in the system. Therefore, to be able to obtain this level of luminous flux from only two LED's, high power LED's should be used. Various types of high power LED's were investigated. Potential LED's that could be used in the structure were analyzed according to their specification datasheets.

2.4 Alternative LED Chip Studies

In the first step, the lumen output level was fixed in LED groups. Then, LED efficiency was defined with respect to target junction temperature 85ºC. At the last step, power consumption of the LED's was calculated according to the defined parameters.

2.4.1 Cree XM-L

The lumen output of Cree XM-L package is 300 lm at 700 mA and 25ºC junction temperature which can be seen in Figure 37. The level of lumen output is decreased to 87.5% at 85 ºC junction temperature. Junction temperature dependence of the luminous flux can be seen in Figure 38. According to the relative luminous flux vs. forward current graph in Figure 39, the driving current should be 1.2 A in order to achieve 812 lm target with 154% increment from the reference lumen output level.

Base Order Codes Min. Luminous Flux @ 700 mA		Calculated Minimum Luminous Flux (lm)*		
Group	Flux (lm)	1000 mA	1500 mA	2000 mA
T5	260	360	511	643
T6	280	388	551	692
U2	300	416	590	742

Figure 37: XML LED luminous flux table [21]

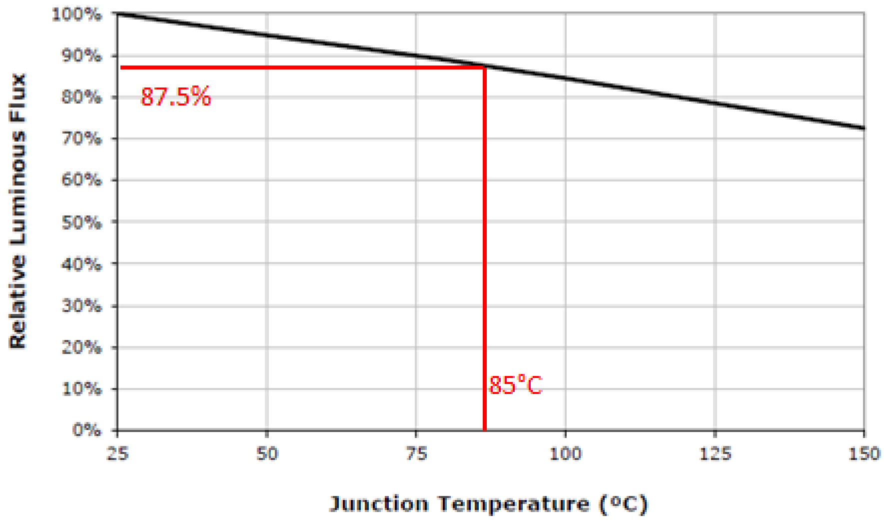


Figure 38: XML Junction temperature – relative luminous flux graph [21]

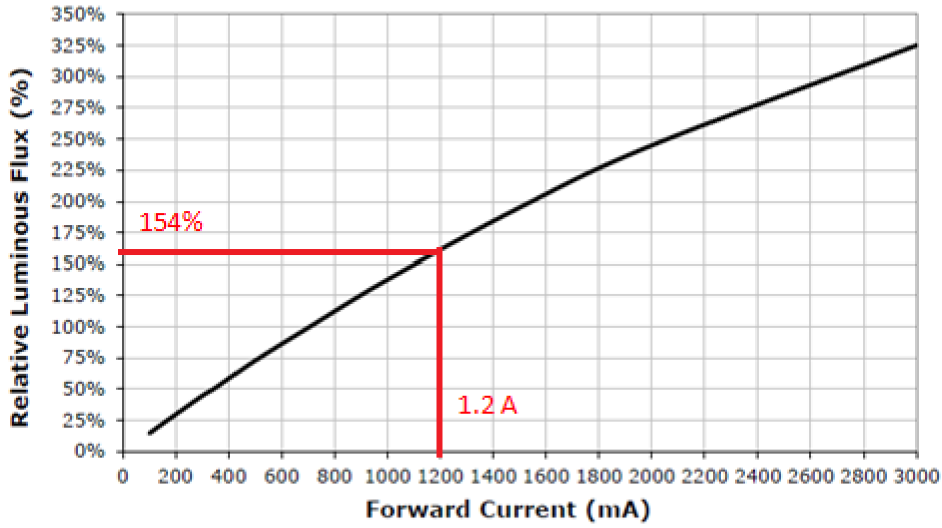


Figure 39: XML Forward current – relative luminous flux graph [21]

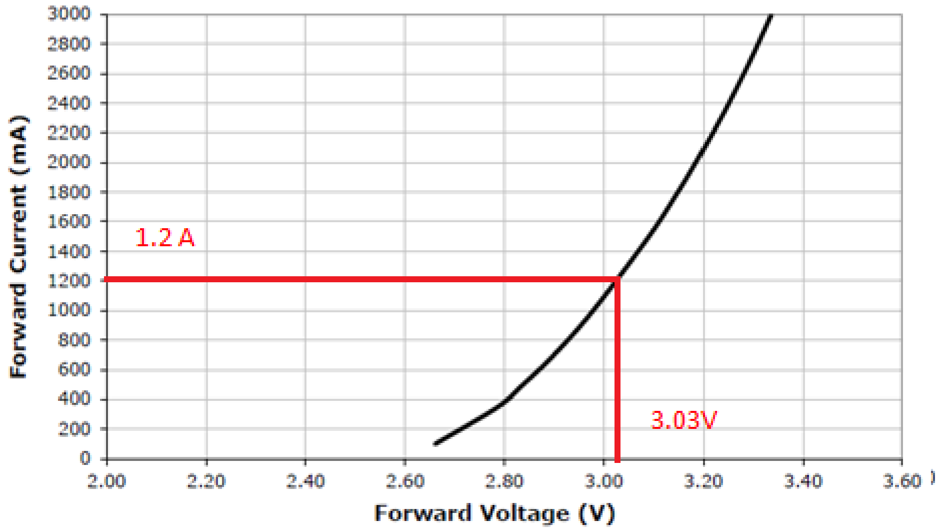


Figure 40: XML Froward voltage vs. forward current graph [21]

When the driving current is 1.2 A the LED forward voltage becomes 3.03 V according to the driving current vs. forward voltage graph of LED in Figure 40. By using formulas 12 and 13 the lumen output and the power consumption of the LED is calculated as 7.27 W under defined conditions.

$$L_{fLED} = L_{ref} * R_{tj} * R_{if} * NoL \qquad (14)$$

Luminous flux calculation

$$L_{fxml} = 300 * 0.875 * 1.54 * 2 = 812\ lm$$

Power consumption calculation

$$PC = I_f * V_f * NoL \qquad (15)$$

$PC_{xml} = 1.2 * 3.03 * 2 = 7.27\ W$

2.4.2 Cree XP-G2

For Cree XP-G2 LED package, while the luminous flux is 158 lm at 350 mA driving current and 25 ºC junction temperature, it drops to 139 lm at 85 ºC junction temperature according to Figure 41. In the specification table, the relative luminous flux level set as 100% at 85 ºC as seen in Figure 42. To be able to achieve the 812 lm targets, 292 % higher output is needed from the base value according the graph in Figure 43.

Base Order Codes Min. Luminous Flux @ 350 mA			Calculated Minimum Luminous Flux (lm)** @ 85 °C		
Group	Flux (lm) @ 85 °C	Flux (lm) @ 25 °C*	700 mA	1.0 A	1.5 A
R3	122	138	223	297	402
R4	130	147	237	316	429
R5	139	158	254	338	458

Figure 41: LED luminous flux table [22]

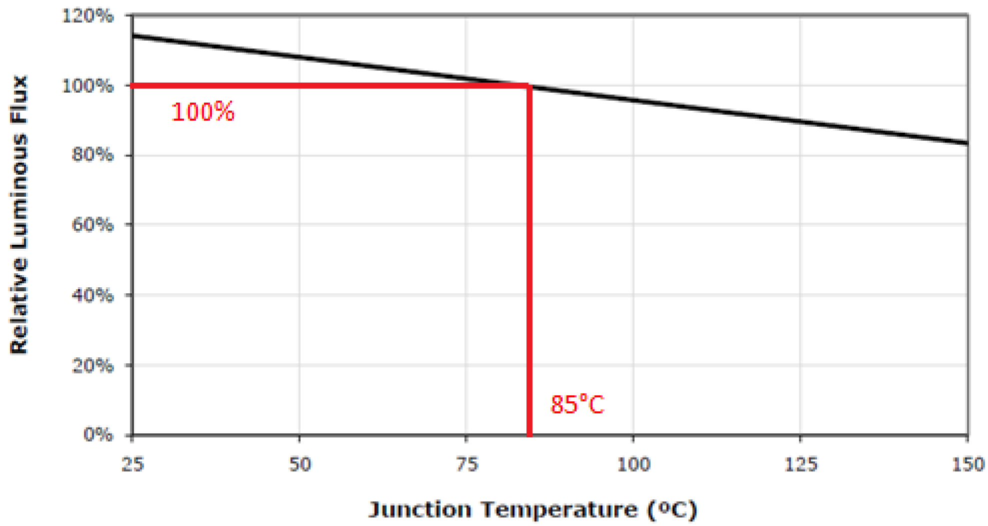


Figure 42: XP-G2 Junction temperature – relative luminous flux graph [22]

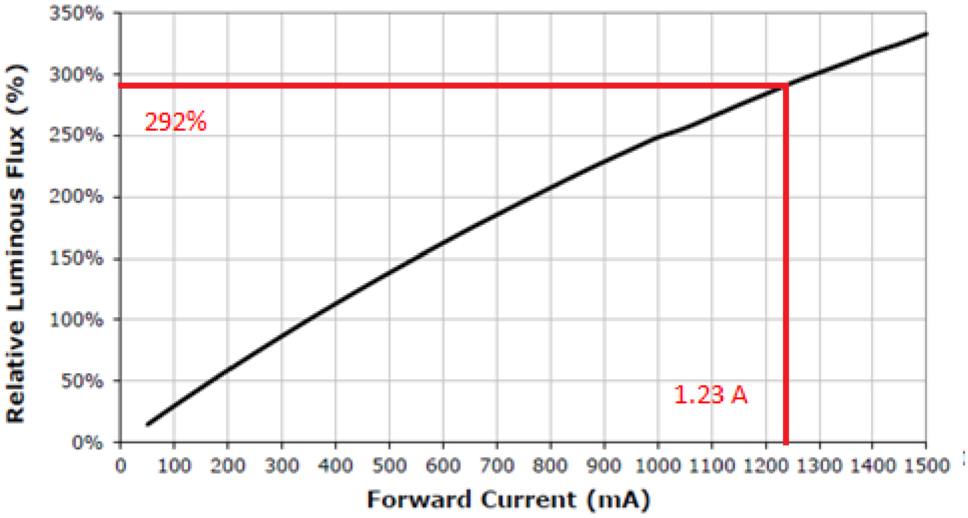


Figure 43: XP-G2 Forward current – relative luminous flux graph [22]

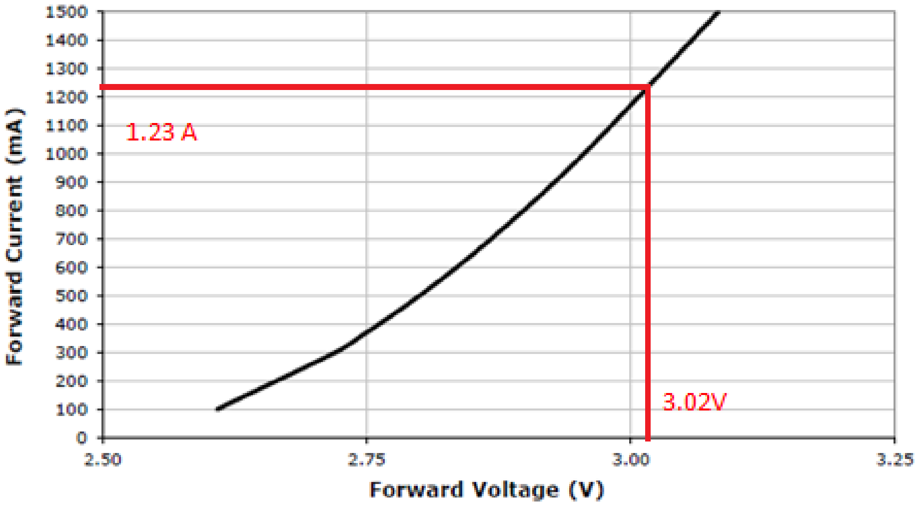


Figure 44: XP-G2 Froward voltage – forward current graph [22]

In order to calculate the power consumption of the LED's, forward voltage – driving current graph in Figure 44 is examined. According to the graph LED forward voltage is 3.02V at 1.23 A driving current. The calculations of lumen output and power consumption with the defined values are represented below. Power consumption of the LED is 7.42 W according to the results.

Luminous flux calculation

$$Lf_{xpg2} = 139 \; * 1.0 * 2.92 * 2 = \; 812 \; lm$$

Power consumption calculation

$$PC_{xpg2} = 1.23 * 3.02 * 2 = 7.42 \; W$$

2.4.3 Cree XT-E

The lumen output of Cree XT-E package is 139 lm at 350 mA and 85ºC junction temperature as seen in Figure 45. The level of lumen output reference is given at 85 ºC junction temperature; therefore the temperature multiplier in the formula is 1 for this LED as given in Figure 46. According to the relative luminous flux, forward current graph in Figure 47, the driving current should be 1.37 A in order to achieve 812 lm target with 292% increment from the reference lumen output level.

Base Order Codes Minimum Luminous Flux @ 350 mA			Calculated Minimum Luminous Flux (lm)** @ 85 °C	
Group	Flux (lm) @ 85 °C	Flux (lm) @ 25 °C*	700 mA	1500 mA
R3	122	140	217	376
R4	130	149	231	401
R5	139	160	247	428

Figure 45: LED luminous flux table [23]

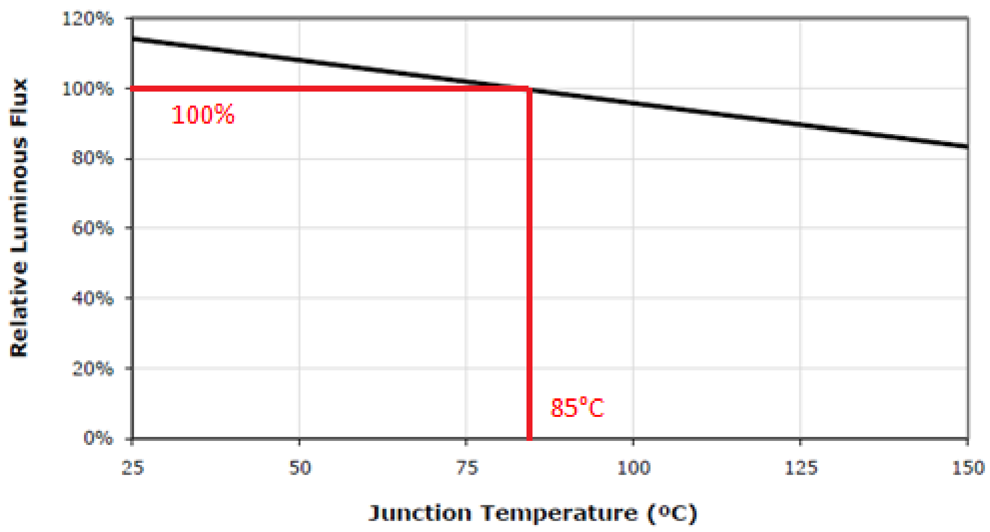


Figure 46: XT-E Junction temperature – relative luminous flux graph [23]

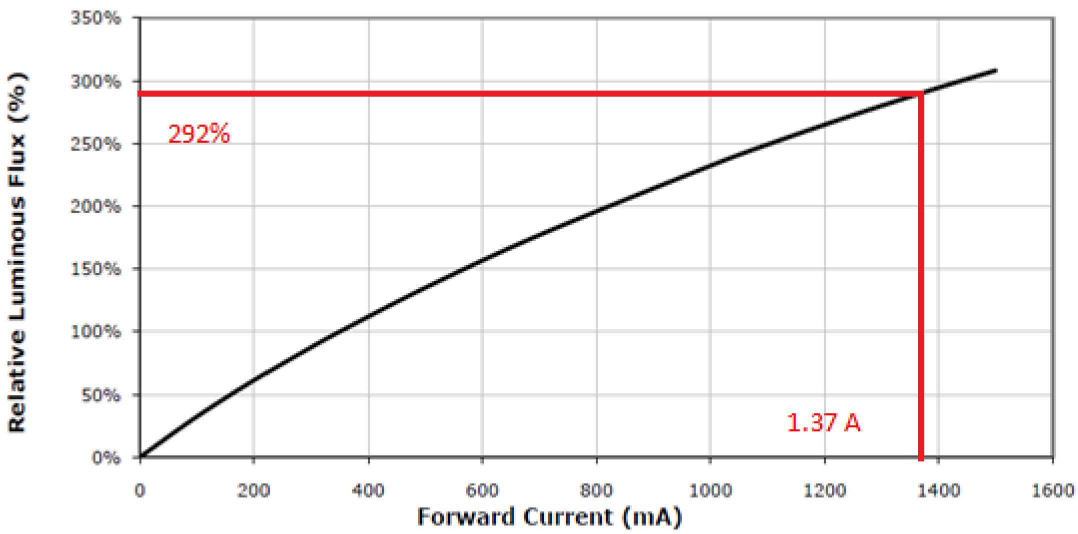


Figure 47: XT-E Forward current – relative luminous flux graph [23]

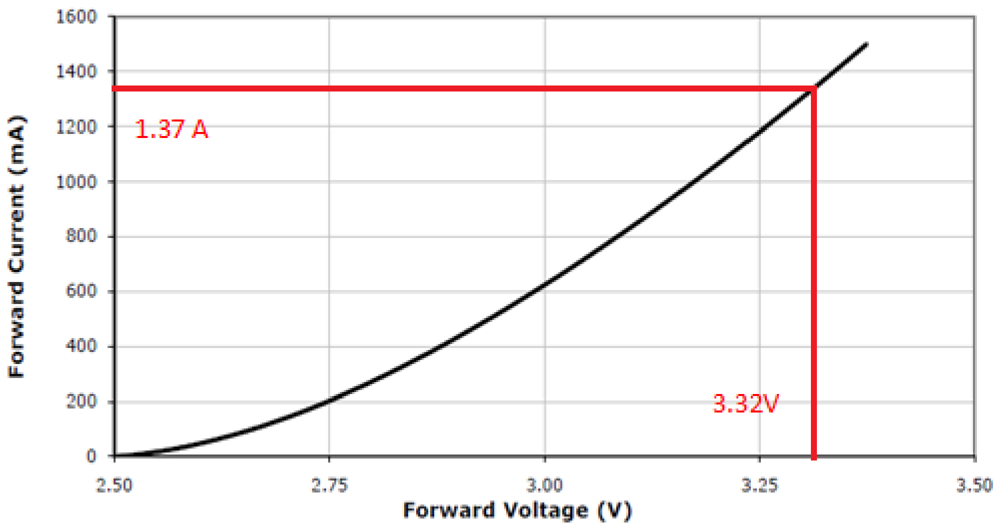


Figure 48: XT-E Froward voltage – forward current graph [23]

When the driving current is 1.37 A the LED forward voltage becomes 3.32 V according to the driving current – forward voltage graph of LED in Figure 48. By using formulas number 12 and 13, the lumen output and the power consumption of the LED can be calculated under defined conditions. The power consumption of the LED is 9.1W according to the calculations.

Luminous flux calculation

$$Lf_{xte} = 139 * 1.0 * 2.92 * 2 = 812\ lm$$

Power consumption calculation

$$PC_{xte} = 1.37 * 3.32 * 2 = 9.10\ W$$

2.4.4 Cree XM-L2

Figure 49 shows the lumen output of Cree XM-L2 level at 0.7 A driving current 85 °C and 25 °C junction temperature levels. At target junction temperature, the lumen output is 300 lm. The relative luminous flux graph is given according to 85°C junction temperature as can be seen in Figure 50. To be able to achieve target lumen output the driving current should be increased to 970 mA according to the relative lumen output – driving current graph as given in Figure 51. This level of driving current provides 1.35 times more flux with respect to reference output.

Base Order Codes Min. Luminous Flux (lm) @ 700 mA		
Group	Flux (lm) @ 85 °C	Flux (lm) @ 25 °C*
T5	260	296
T6	280	318
U2	300	341

Figure 49: LED luminous flux table [24]

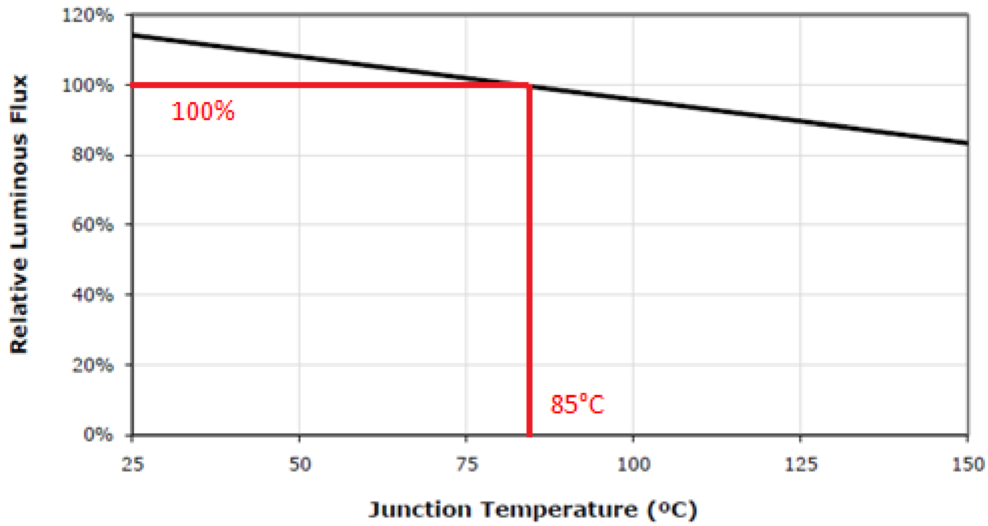


Figure 50: XM-L2 Junction temperature – relative luminous flux graph [24]

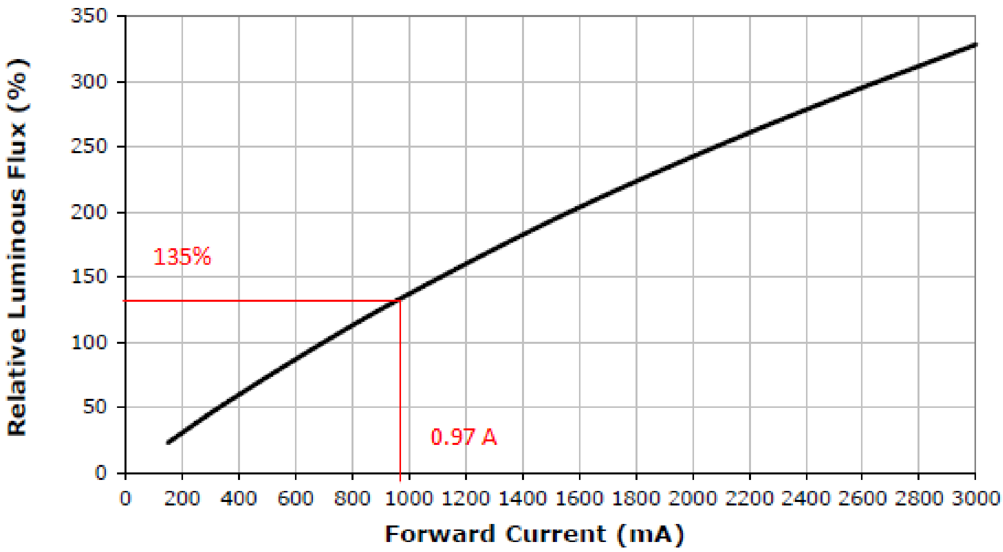


Figure 51: MT-G2 Forward current – relative luminous flux graph [24]

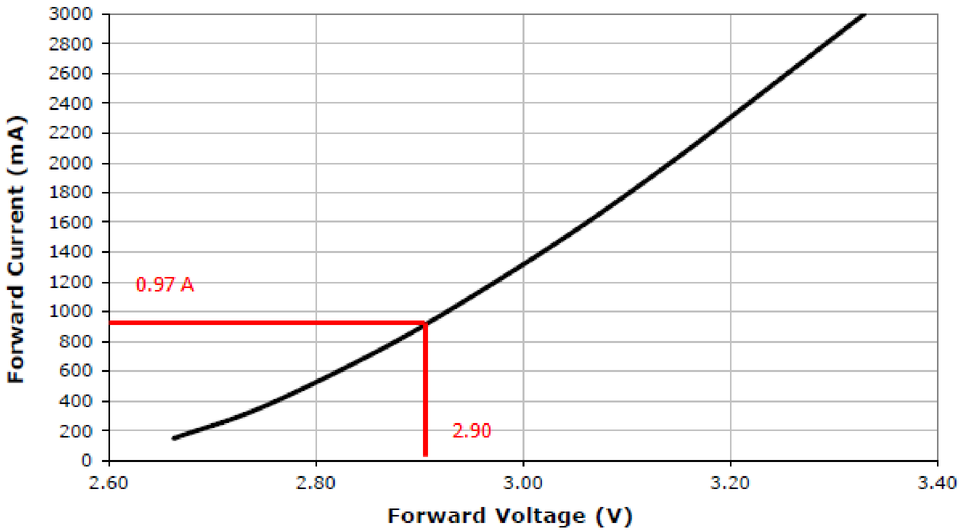


Figure 52: XM-L2 Froward voltage – forward current graph [24]

Figure 52 shows the forward voltage dependency on driving current graph of the LED. According to the graph forward voltage is 2.9 V for 0.97 A driving current. When the calculation is performed the power consumption is found as 5.63 W.

Luminous flux calculation

$$Lf_{xpg2} = 300 \ * 1.0 * 1.35 * 2 = \ 812 \ lm$$

Power consumption calculation

$$PC_{xpg2} = 0.97 * 2.90 * 1 = 5.63 \ \ W$$

Table 11: Properties and Calculated design parameters of the examined commercial LEDs

Properties	**Unit**	**XML**	**XP-G2**	**XT-E**	**XM-L2**
Thermal res. from junction to solder	°C/W	2.5	4	5	2.5
Beam angle (FWHM)	°	125	115	115	125
Temp. coefficient of forward voltage	mV/°C	-2.1	-1.8	-2.5	-1.6
DC forward current	mA	3000	1500	1500	3000
Max LED junction temperature	°C	150	150	150	150
Design Parameters					
Driving current	mA	1200	1230	1370	970
Forward voltage	V	3.03	3.02	3.32	2.9
Luminous flux	lm	812	812	812	812
Number of LED’s	-	2	2	2	2
Power consumption	W	7.27	7.42	9.1	5.63

Table **11** shows the properties of the LED’s and the calculated results. All calculations were performed in order to have the same optical results; therefore, while choosing the appropriate LED for the design thermal properties should be taken into consideration. Cree XM-L2 has the lowest power consumption and lowest thermal resistance from junction to thermal pad as 3.5 ºC/W. Therefore, optical simulations with Light Tools will be started with XM-L2.

CHAPTER 3

OPTICAL MODELLING

After finalizing the optical component studies, optical design for LED placement and LGP patterning studies were performed in Light Tools simulation program. First of all, Cree XM-L2 LEDs are placed in the BLU. The location and the placement of the LEDs are given in the Figure 53.

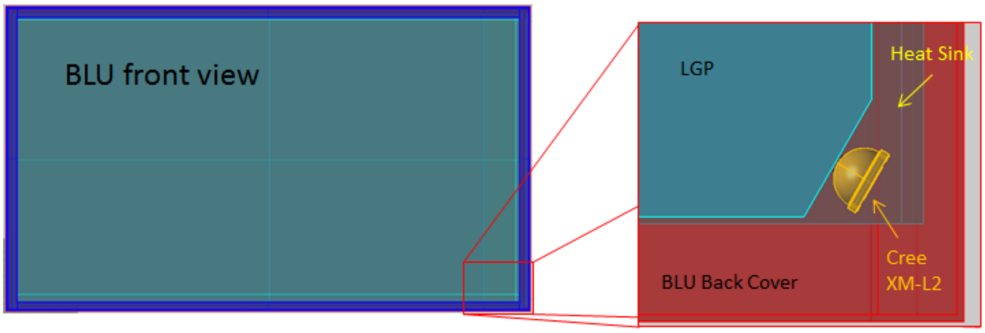


Figure 53: Corner LED placement in the BLU

3.1 Light Tools Parameters

In order to run an optical simulation in Light Tools, some optical parameters should be defined in the program. The definition of these parameters are listed and explained in the items below.

3.1.1 Optical properties

Light Tools optical property section and possible optical property options can be seen in Figure 54. Following optical properties are selected for this study. Middle frame and metal back-cover of the panel is defined as the mechanical absorbers. PCB of the LEDs is defined as smooth optical with 80% reflectance and 20% absorbance. LGP is made out of PMMA which has 92% transmittance property. Therefore the LGP optical property is set as 92% transmittance in smooth optical property section.

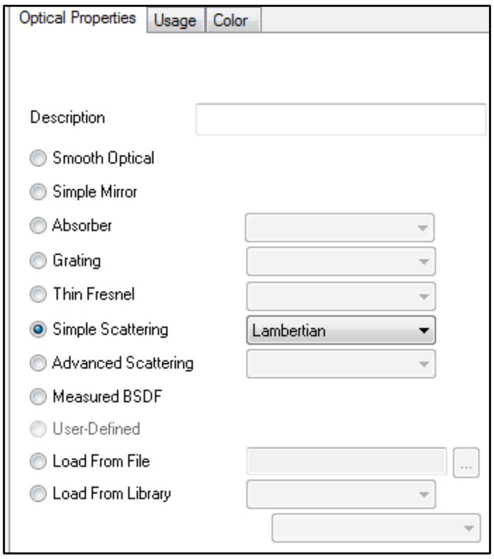


Figure 54: List of possible optical properties on Light Tools

Side reflectors of the LGP are defined as Gaussian simple scattering which has 95% reflectance, 3 scattered rays and 16.9° Gaussian spread sigma degree. Reflector sheet of the system is also defined as Gaussian scattering. Properties of reflector sheet are 95% reflectance, 5 scattered rays and 2.1° Gaussian spread sigma degree.

One of the most critical optical properties is LGP pattern ink because it affects all light distribution and pattern density of the LGP. Pattern (texture) property is defined as complete scattering in the advanced scattering section. The details of the optical property of ink can be seen in Figure 55.

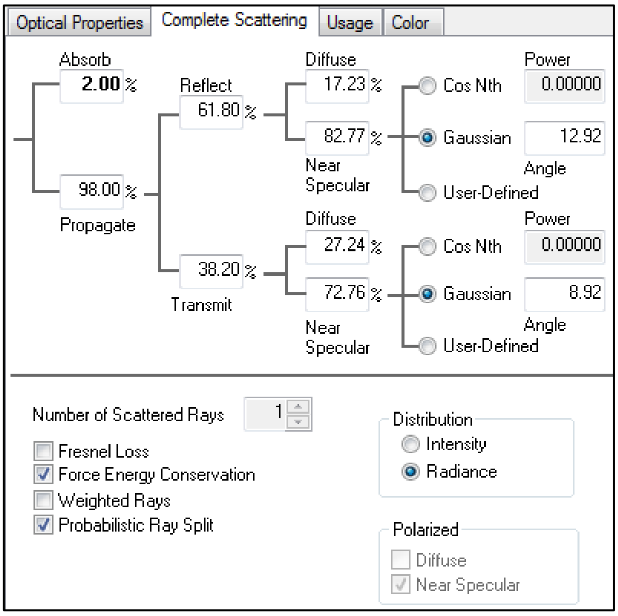


Figure 55: Optical property details of LGP pattern (texture)

3.1.2 LGP Pattern (Texture)

Center luminance, luminance uniformity and visual performance of the TV are adjusted by LGP pattern distribution. Pattern of the LGP is printed at the back surface of the LGP. The geometry options of the texture can be seen in Figure 56.

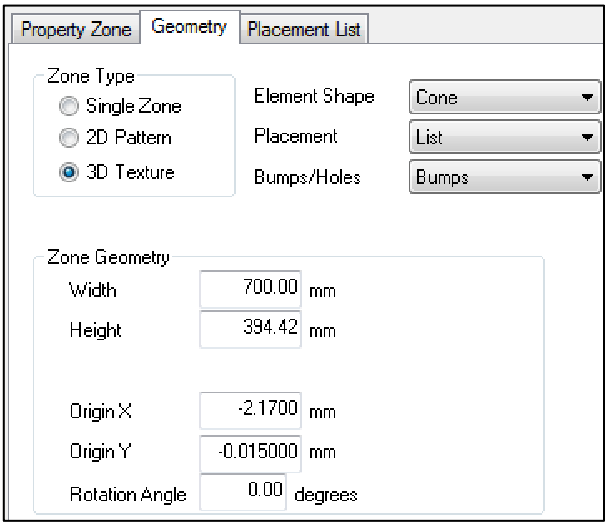


Figure 56: The geometrical properties of the LGP texture

The pattern is applied on to the LGP by using a reflective and diffusive ink with the help of a screen mask. The production of the LGP pattern can be defined as optical grade silkscreen printing. Due to circle shape of the mask holes the pattern shape is became cylinder. In order to create cylinder patterns, zone type should be defined as 3D texture and element shape should be defined as cone bumps element in Light Tools. The zone geometry of texture is determined according to the active area of the BLU which is the inner side of the middle frame. It can be referred to Figure 57 for the definition of the active area. Middle frame is shown translucent in order to understand the borders of the components in the figure. Some part of the middle frame covers the LGP. The texture should be created at the active area of the LGP for not to have light loses in the inactive part of the TV. Zone geometry of the texture is determined according to this specification.

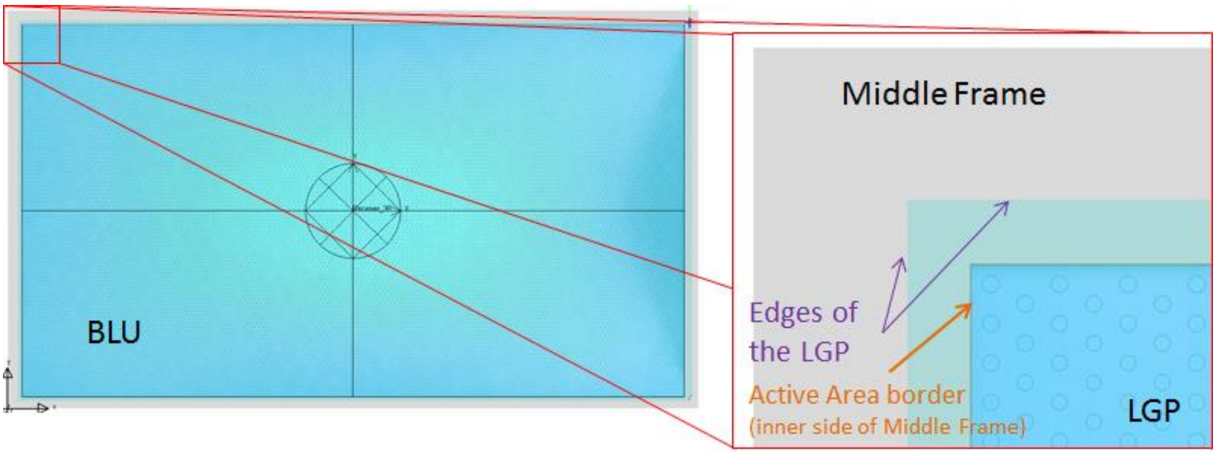


Figure 57: BLU middle frame and LGP texture area definition

Cone shape can be configured in the cone element section of the Light tools which can be seen in Figure 58. A and B radiuses of the cone element should be same for make the cone cylinder. The height of pattern is determined according to the screen mask thickness which is 0.007 mm.

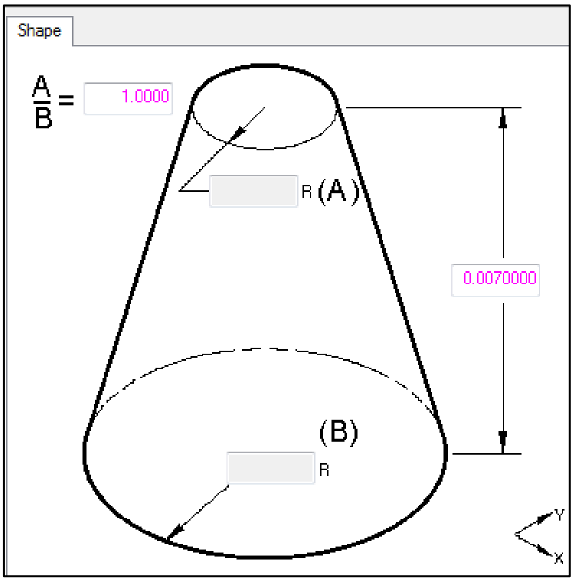


Figure 58: The cone element geometrical properties of the LGP texture

Dot placement of the texture is defined as hexagonal and the size is defined as variable. It can be referred to the Figure 59 for the placement of the texture. The distance between dot centers are called as x pitch and y pitch.

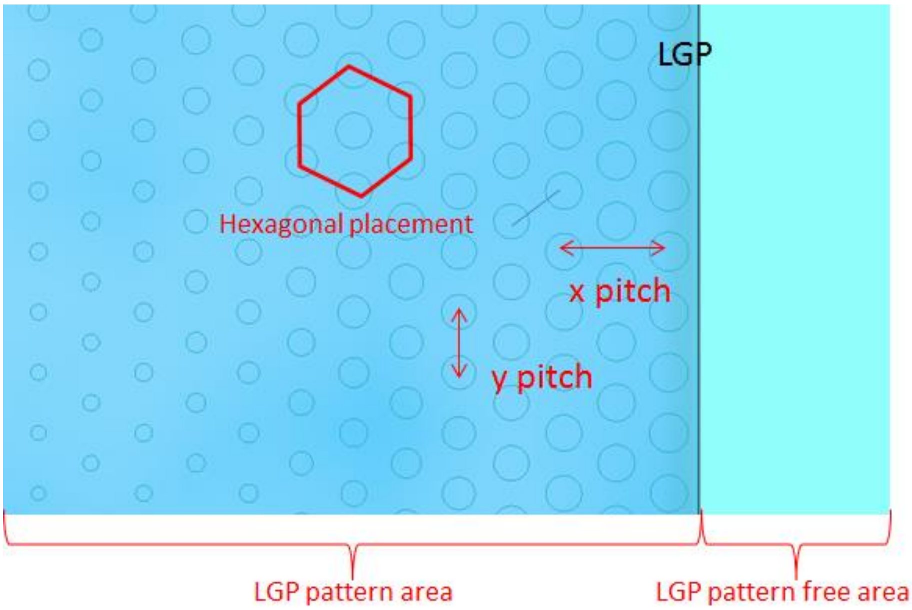


Figure 59: Definitions of the LGP texture properties.

The x pitch is defined as 2.35 mm and y pitch defined as 2.7 mm. In order to prevent dot overlaps and to keep the screen mask quality high, the minimum distance between dots is determined as 0.15 mm and minimum dot radius is defined as 0.1 mm. Under these conditions, the dot radius can be increased up to 1.275 mm.

3.1.3 Uniformity Target

The spatial luminance receiver is created on the front surface of the TV panel for measuring the center luminance and luminance distribution. The receiver is placed on a dummy surface which has the same rectangular dimensions with LGP texture area. The receiver is placed 2 mm distance from the display surface. In order to have the correct data, photometric flux option is selected in unit section as can be seen in Figure 60.

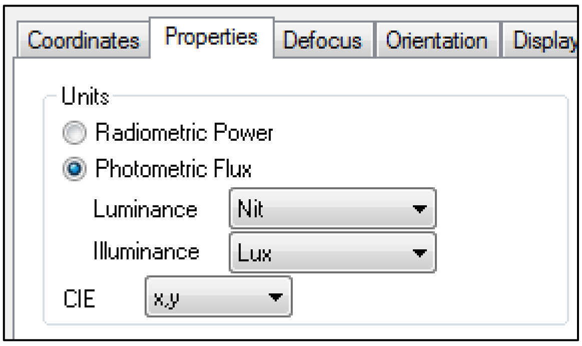


Figure 60: Receiver properties of the system

The mesh count of the spatial luminance meter is defined as 121 x 71 matrix, which refers to 5.78 mm x 5.40 mm cell dimension for each luminance result section, for measurement result analysis. In order to achieve center luminance and uniformity design targets, an ideal luminance distribution is defined for 121 x73 mesh. The graph of the luminance distribution target can be seen in Figure 61. Luminance distribution will be smooth and decreased to the edge of the display with the help of this matrix. This technique will let the usage of light in the center more than other parts. In other words, the optical efficiency of the display increases.

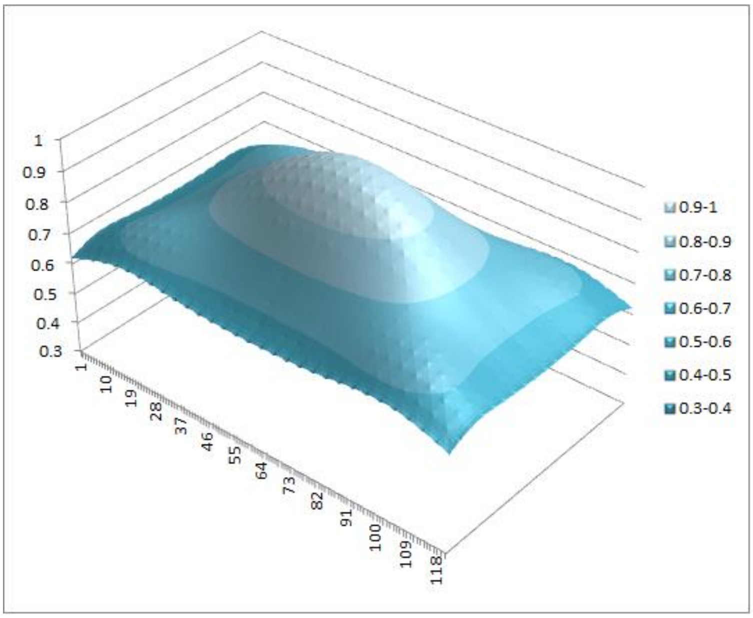


Figure 61: Luminance distrubution target of the display.

Light sources of the system are set as 406 lm photometric flux which is measured over aim region. The angular distribution of the LEDs is very close to Lambertian distribution therefore specific LED distribution is not defined. The emittance settings of an LED can be seen in Figure 62.

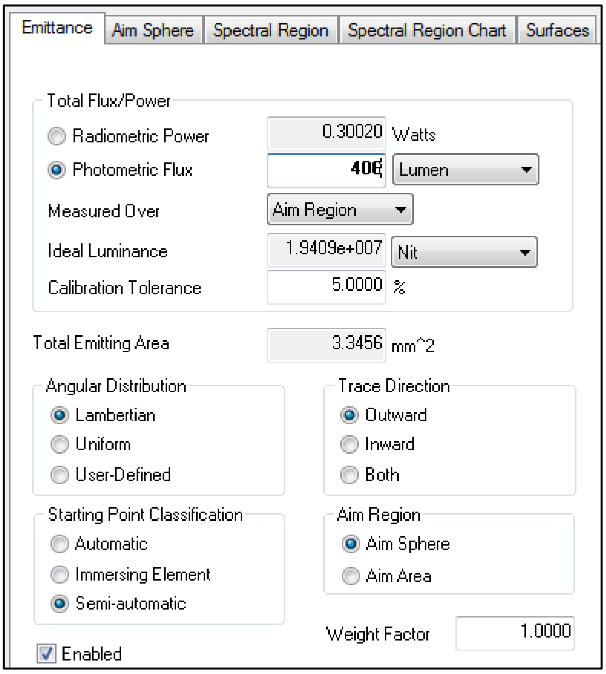


Figure 62: Emittance properties of the LEDs

Light emittance distribution and the direction of the LEDs are defined in Aim Sphere tab of the light source property window. Light emittance is confined to the front surface of the LED by setting lower angle to 90° in order to create lambertian distribution. And, LED direction is defined as 60° to position the LED for the highest optical efficiency to be able to transfer the light to far shorter edge of the LGP. Light tools representation of the aim sphere is shown in Figure 63.

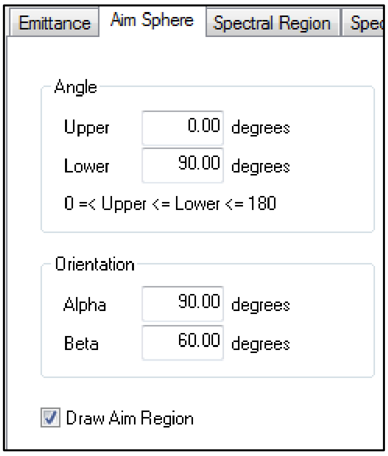


Figure 63: Geometrical properties of the light source

Some of the critical parameters of the Light Tools simulation are listed in the Table 12.

Table 12: Critical parameters of Light Tools setup for corner-lit display

Parameters	Value
LGP Pattern Texture x (mm)	700
LGP Pattern Texture y (mm)	394.42
Texture Zone Type	3D
Texture Element Shape	Cone / Bumps
Placement	Hexagonal
Texture Dot x pitch (mm)	2.35
Texture Dot y pitch (mm)	2.70
Min Cone Radius (mm)	0.1
Max Cone Radius (mm)	1.275
Cone Height (mm)	0.007
Receiver x (mm)	700
Receiver y (mm)	394.42
Receiver distance from Display (mm)	2
Receiver Mesh x	121
Receiver Mesh y	73
Mesh cell x dimension (mm)	5.78
Mesh cell y dimension (mm)	5.40
Number of rays	20 Million

3.2 Application of Commercial LED Packages in the Optical Models

3.2.1 Cree XML2 Corner

After finalizing the LED initial evaluations, Cree XM-L2 LED is seemed appropriate for the corner LED solution. The LEDs are placed at the right-top and right-bottom corners of the BLU. The LED placements are symmetrical at the top and bottom corners. The front view of the 32" BLU and zoomed in view of the LED at the right bottom corner can be seen in Figure 64. The corner view is presented without plastic middle frame for better inspection of LED placement.

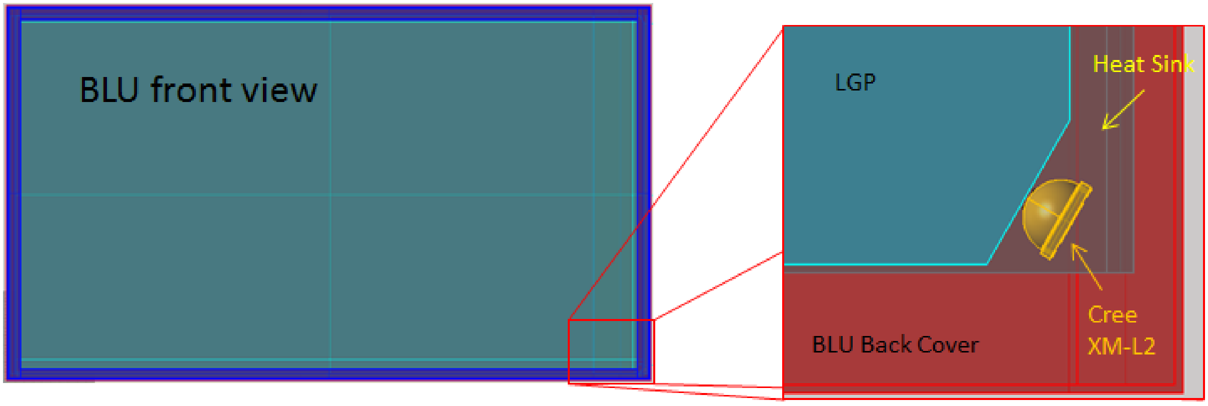


Figure 64: The placement of the Cree XM-L2 in the display.

When the simulation is run with the specified parameters in the previous section and without any LGP pattern study, the luminance distribution of the display is concentrated at the two corners of the display as can be seen in Figure 65.

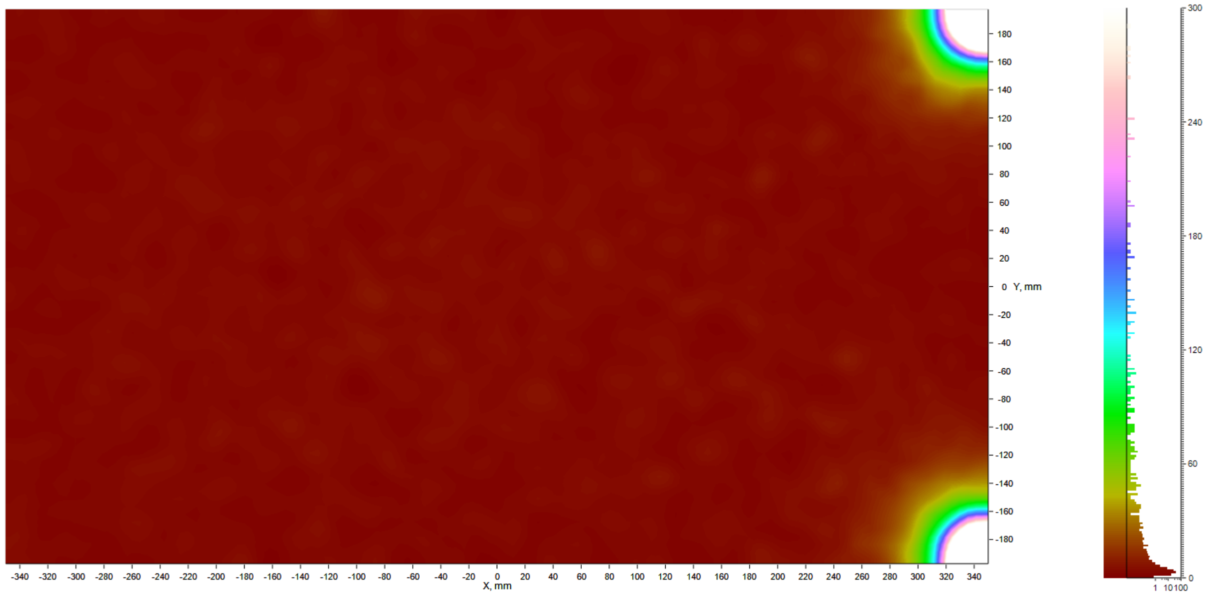


Figure 65: Luminance distribution result of the Cree XM-L2

When this result is closely examined, a possible light leakage is expected in the system. Because the light beams should not go out without any pattern studies. If there is any light leakage in the system, the light at the leakage cannot be controlled with the LGP pattern. Therefore, the root cause of the light leakage should be defined. The problem mechanism can be understood by checking the mechanical structure of the design. The bottom side view of the inner side of the BLU can be seen in Figure 66. The LED TV's in the market are slim; therefore there are dimensional limits in terms of thickness of the components. For example LGP thickness should not exceed 3 mm. Cree XM-L2 LED dimension is too big for 3 mm LGP, therefore some of the light leakage from the optical film side of the system can be seen in Figure 66. Under these dimensional conditions, it is not possible to direct the light in to the LGP from these LEDs. A secondary optical component should be defined to solve the problem.

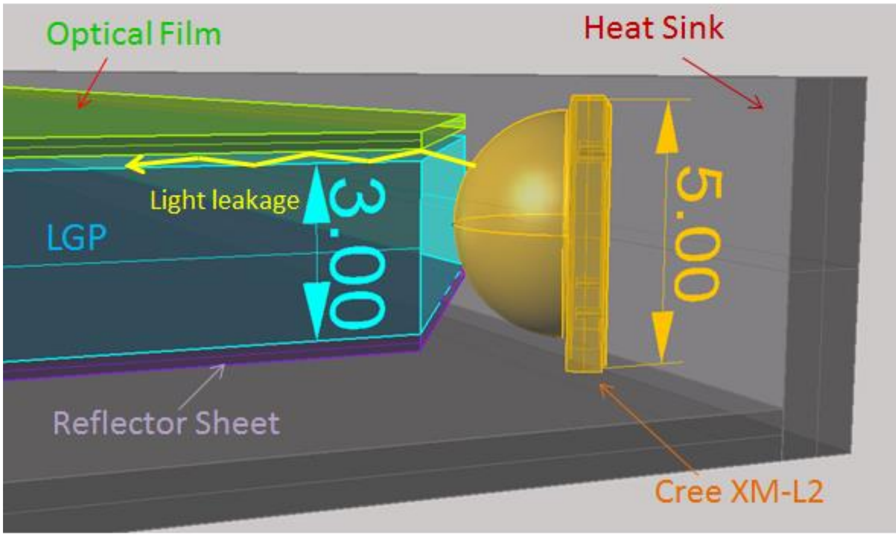


Figure 66: Cross-sectional view of XM-L2 and LGP placement

3.2.2 Cree XML2 Corner with Light Tube

A light guide tube (LGT) is defined for XM-L2 LEDs as a secondary optical component. The placement of the bottom LED and LGT can be seen in Figure 67. In order not to lose the wide angle beams a reflector sheet is defined around the LEDs in addition to the LGT.

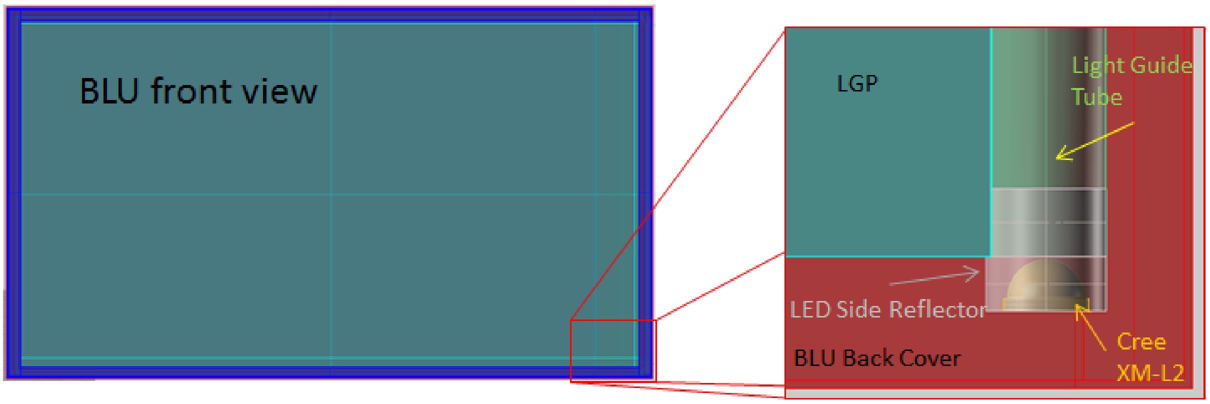


Figure 67**:** The placement of the Cree XM-L2 and light guide tube in the display.

Bottom dimensions of the LED are 5 mm by 5 mm; therefore LGT is defined as cylindrical shape. The radius of the cylinder is chosen 7.1 mm to keep the LED light inside. The LGP side of the LGT is trimmed for the best coupling with the LGP. The detailed LED, LGT, LGP placements and LGP coupling surface can be seen in Figure 68.

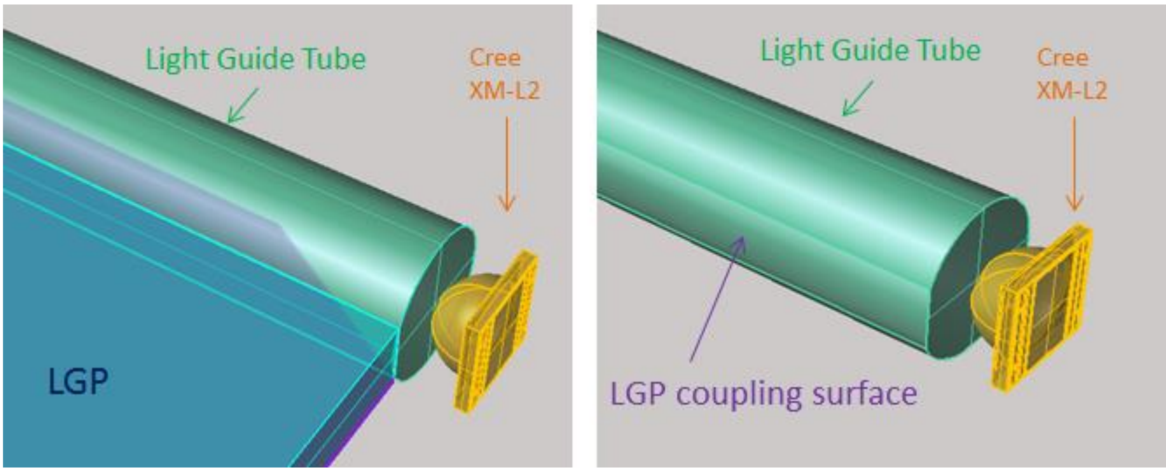


Figure 68: Angular view of XM-L2, LGT and LGP placement. LGP coupling surface of LGT

To be able to efficiently direct the LED light into the LGT, a cylindrical shape reflector is defined around the LEDs. Reflector shape is a regular cylinder starting from the bottom side of the LED, until the LGP coupling surface. In order not to block the light directed to the LGP, an opening is defined on the reflector shape. Figure 69can be referred for the detailed LGT reflector shape.

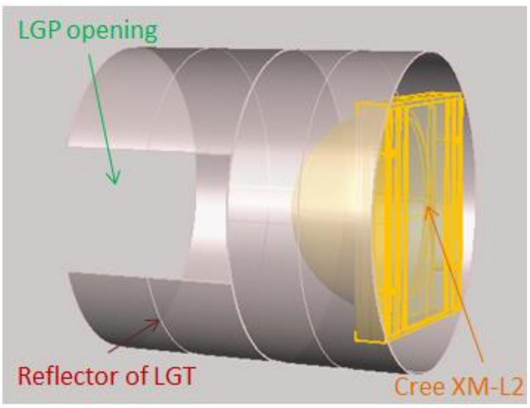


Figure 69: LED side reflector and LED’s ghost shell view.

In order to direct the light in to the LGP from LGT, total internal reflection should be disturbed by reflective surfaces around the LGT along the vertical direction of the panel. After finishing the optical structure of the BLU, LGP pattern study is performed for achieving the luminance distribution targets. The final dot size distribution can be seen in Figure 70 left hand side. The light distribution cannot be perfect with 20 million rays; therefore, there is a noisy dot size distribution. To be able to get a better distribution for real application three by three matrix low pass filter is applied to the distribution result. Right hand side of Figure 70 shows the result after applying the low pass filter.

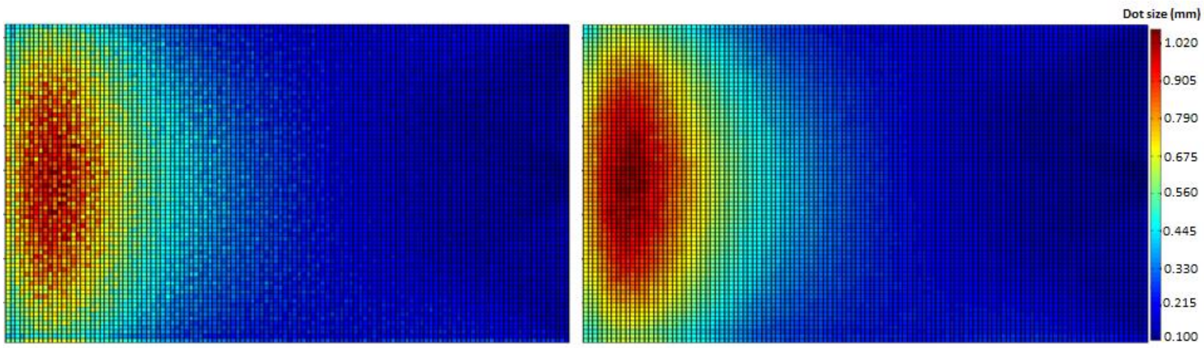


Figure 70: (a) Dot size distribution of LGP texture of XM-L2 and LGT. (b) 3x3 low pass filtered LGP pattern

After finalizing the pattern study for the structure, spatial luminance distribution of the panel become as seen in Figure 71. General visual performance is obtained to be satisfactory but the maximum calculated luminance is 201 nits which is lower than expected and it needs improvement. Luminance uniformity of 9 points' results can be seen in the Table 13. The 9 points luminance uniformity is 77% which is 2% higher than target spec. However the center luminance is only 198 nits which is 20% lower than target luminance 250 nits.

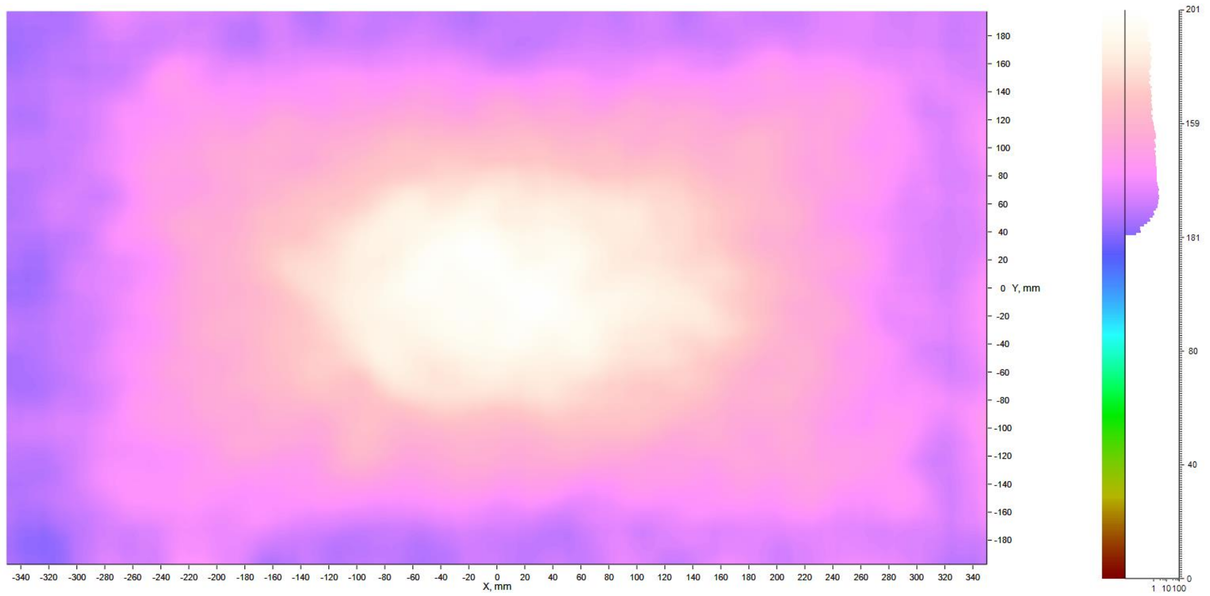


Figure 71: Luminance distribution findings of a Cree XM-L2 and LGT

Table 13**:** Luminance uniformity results of Cree XM-L2 and LGT design

9 Points Luminance Uniformity Results			
	H/4	H/2	H/4
V/4	155	166	162
V/2	161	198	171
V/4	155	164	153

9 Points Luminance Uniformity Ratios			
	H/4	H/2	H/4
V/4	78%	84%	82%
V/2	82%	100%	87%
V/4	78%	83%	77%

3.3 Alternative LED chip studies for mechanical compatibility

According to the results, LED dimensions should be decreased under 3 mm LGP thickness to be able to increase the optical efficiency. It will decrease the optical loses but lumen output of two LEDs cannot reach the target level 812 lumens. LEDs available on the market are examined for the design purpose. After the examination two LEDs, which can reach the desired luminous flux value and has appropriate mechanical dimensions are determined. Luminous design with two LEDs has been inadequate because of the smaller size of the chips.

For this reason, the number of LEDs used in the design has been increased to four. XBD LED from Cree Company and Luxeon Z-ES LED from Philips Lumileds company are intended to be used in the design. Suitability assessment calculations of these two LEDs are given below.

3.3.1 Cree XBD

The luminous flux of Cree XBD LED package at 700 mA and 1000 mA can be seen in Figure 72. Mechanical dimensions of the XBD LEDs are 2.45 mm x 2.45 mm as seen in the Figure 73. These dimensions provide suitable conditions for the direct entry of light in to the 3.00 mm LGP.

Base Order Codes Min. Luminous Flux @ 350 mA			Calculated Minimum Luminous Flux (lm)**	
Group	Flux (lm) @ 85 °C	Flux (lm) @ 25 °C*	700 mA	1000 mA
R3	122	139	210	271

Figure 72: XBD LED groups [25]

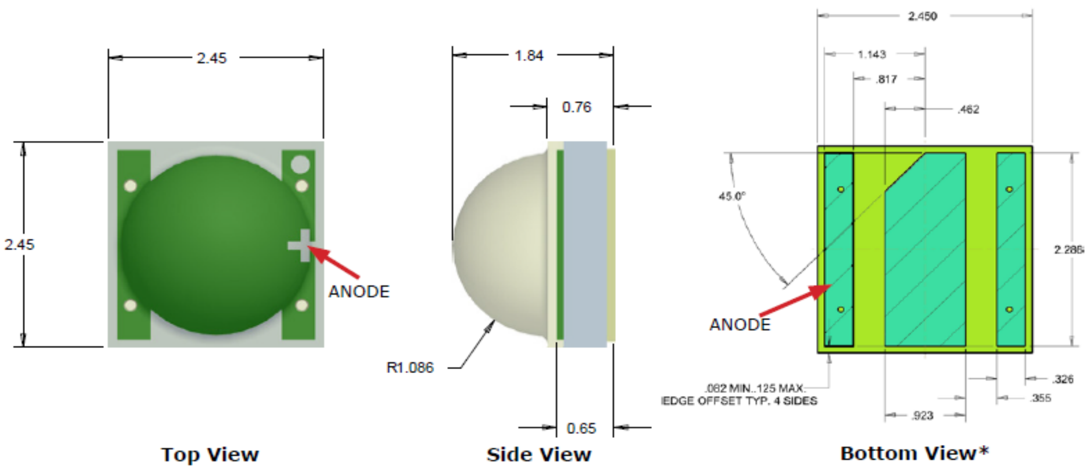


Figure 73 Mechanical dimensions of CREE XBD package [25]

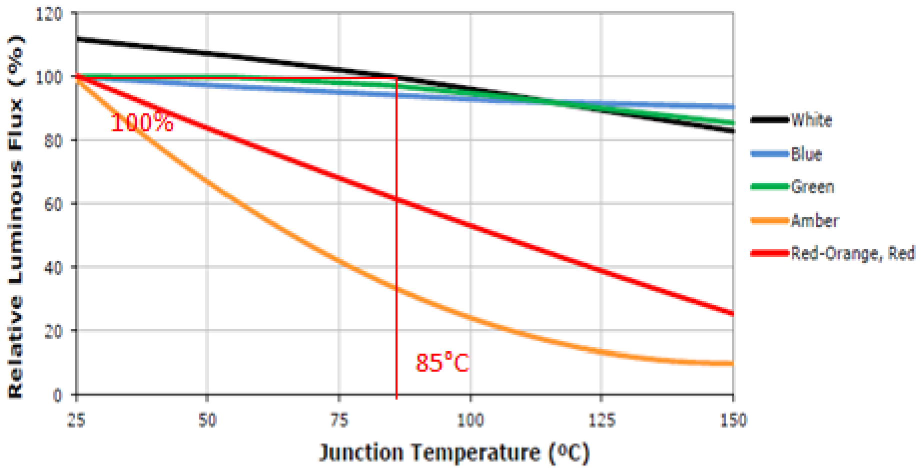


Figure 74: : Luminous flux graphic according to XBD junction temperature [25]

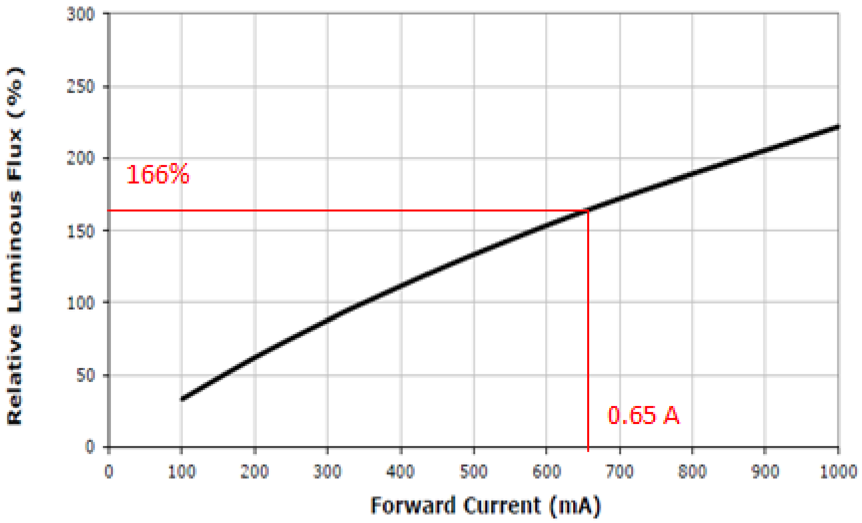


Figure 75: Voltage-current curve of XBD [25]

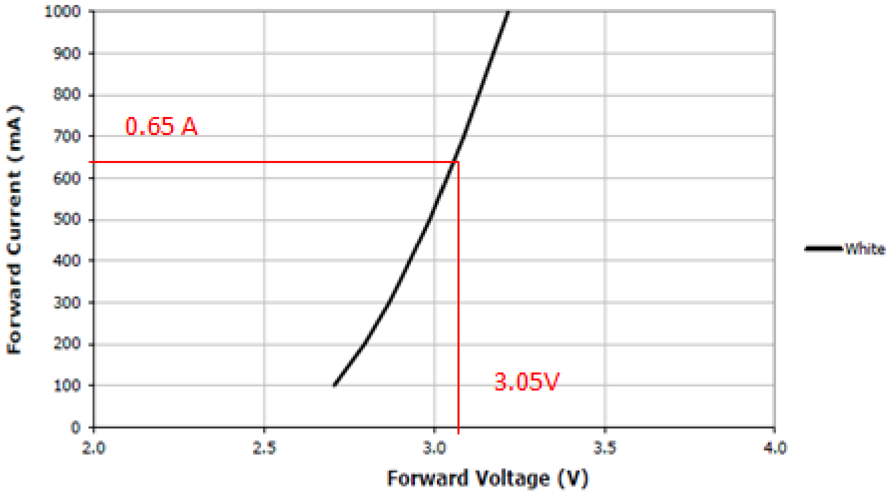


Figure 76: Luminous flux change of XBD according to current [25]

Calculation of the luminous flux is performed as follow by using the formula number 12 and 13 ;

Luminous flux calculation

$$Lf_{xbd} = 122 * 1.0 * 1.66 * 4 = 812\ lm$$

Calculation of Power Consumption

$PC_{xbd} = 0.65 * 3.05 * 4 = 7.93\ W$

The temperature to be reached at the welding point is determined as 72.1 °C. This value is calculated by using heat resistance between LED junction and solder point after the power consumption calculation in the formula number 14.

Calculation of expected solder point temperature:

$$T_{sp} = \mathrm{T_j} - (\mathrm{PC} * \mathrm{R_{th}}) \tag{16}$$

$R_{th} = 6.5\ °C/W$

$\boldsymbol{T_{sp}} = \mathbf{85} - (1.98 * 6.5) = 72.1\ °C$

3.3.2 Lumileds Luxeon-Z-ES

Next LED package is chosen from Philips/Lumileds company. Their high power LED series offer a number of alternatives. The luminous flux of Luxeon-Z-ES LED at 700 mA can be seen in Figure 77.

@ 700 mA		
Min Flux (lm)	Typ flux (Lm)	Typ. Vf
200	215	2.85

Figure 77: Luxeon Z-ES LED groups [26]

Mechanical dimensions of the Luxeon Z-ES LEDs are 1.64 mm x 2.04 mm as seen in Figure 78. These dimensions provide suitable conditions for the direct entry of light in to the 3.00 mm LGP. In addition, for a further development these LEDs allow to use 2.00 mm LGP by placing 1.64 mm side of the LED along the thickness of the LGP. In this way, a thinner TV structure can be obtained. Furthermore, cost advantage can be provided by less usage of PMMA (Poly Methyl Methacrylate – Plexiglas) which is the raw material of LGP.

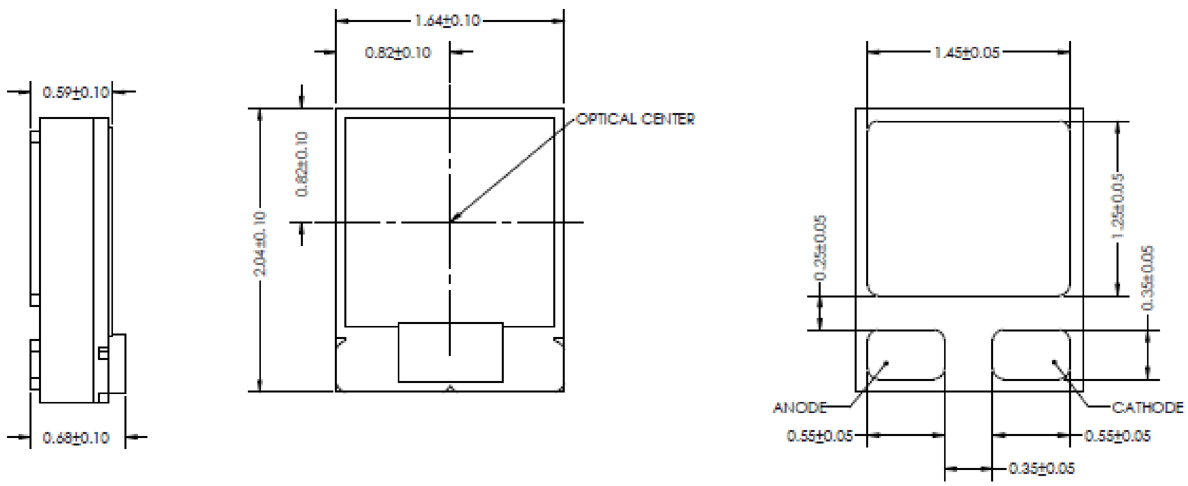


Figure 78: Mechanical dimensions of Luxeon Z-ES package [26]

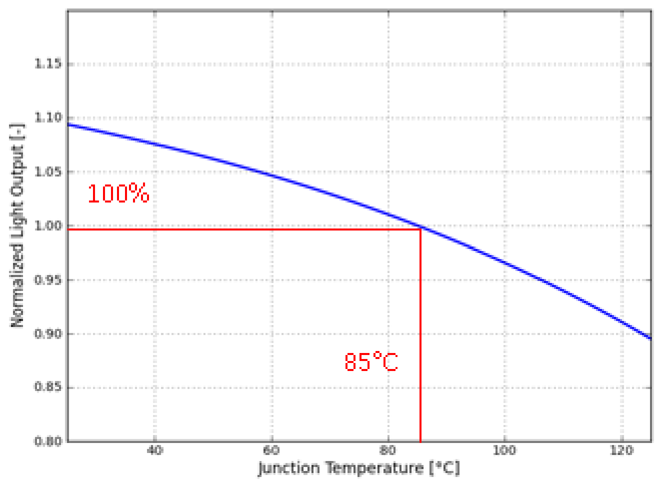


Figure 79: Luminous flux graphic according to Luxeon Z-ES junction temperature [26]

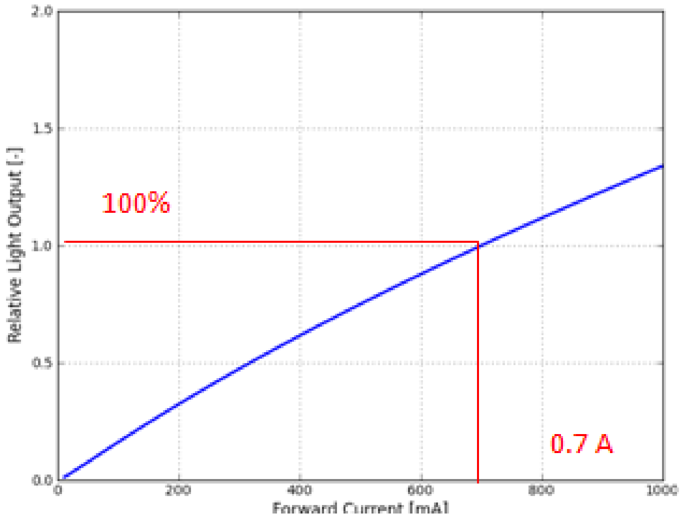


Figure 80: Voltage-current curve of Luxeon Z-ES [26]

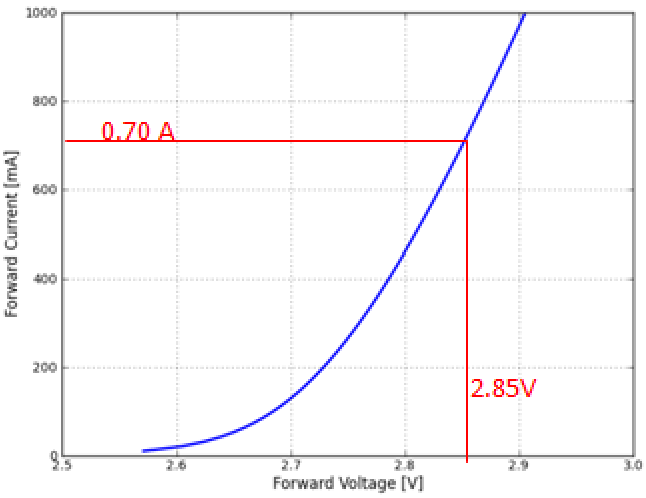


Figure 81: Luminous flux change of Luxeon Z-ES according to current [26]

Calculation of Luminous Flux

$$Lf_{L-zes} = 204 \ * 1.0 * 1.0 * 4 = \ 812 \ lm$$

Calculation of Power Consumption

$$PC_{L-zes} = 0.7 * 2.85 * 4 = 7.98 \ W$$

Temperature is expected to reach at the solder point determined as 79 °C. This value is calculated by using heat resistance between LED junction and solder point after the power consumption calculation.

Calculation of solder point temperature

$R_{th} = 3\ °C/W$

$T_{sp} = 85 - (1.99 * 3) = 79\ °C$

3.4 Corner Lighting Application Optical Models

New concept has been studied over a variety of commerically available LED chips and packages. The following section describes the results of the optical models for each of those possible implementations.

3.4.1 Cree XBD Corner with Light Tube

LED direction can be adjusted directly into the LGP from the corner. In order to compare the optical efficiency of optical design with LGT and direct corner-lit, firstly LGT design is adapted to the Cree XBD LEDs. As shown in Figure 82, two XBD LEDs are placed to each two corners like Cree XM-L2 LEDs.

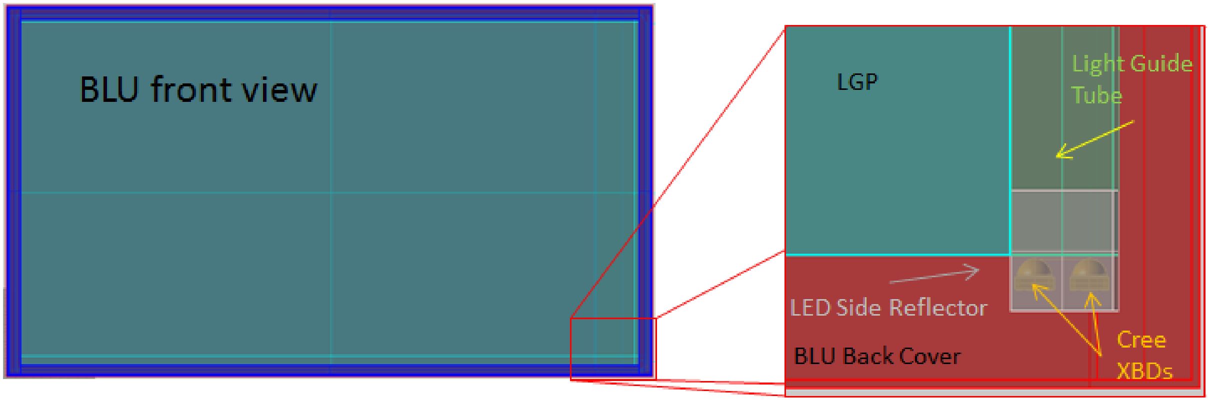


Figure 82: The placement of the Cree XBD and light guide tube in the display.

LGT dimensions are decreased from 7.1 mm to 3.0 mm according to LGP thickness for higher optical efficiency in this design. The cross sectional view of the LEDs, LGT and LGP is shown in Figure 83. Because of the geometrical limitations, one of the LEDs is placed farther away from the LGP which cause light loses.

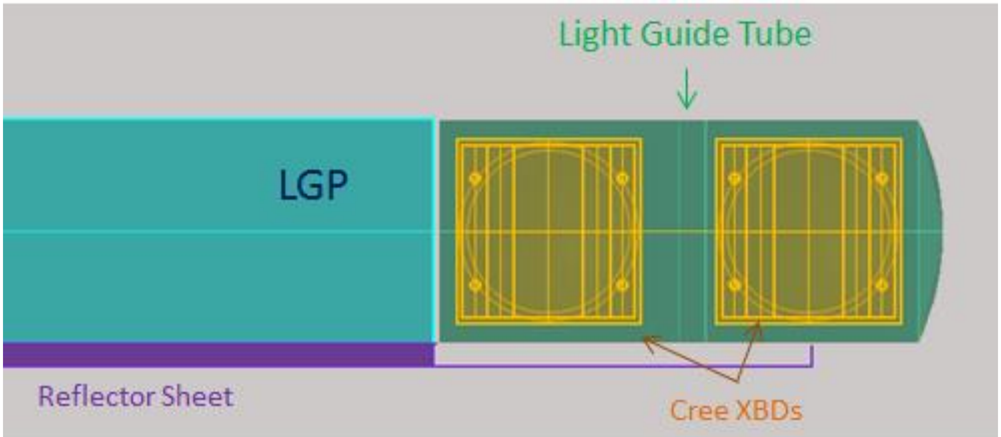


Figure 83: Cross-sectional view of LEDs, LGT and LGP

After finishing the optical structure studies, LGP patterning studies are finalized for achieving the center luminance and luminance uniformity targets of the TV. The dot size distribution of the LGP is shown in the left hand side of Figure 84. The 3 by 3 low pass filtered pattern can be seen in the right hand side of Figure 84. The achieved luminance of the center point is 233 nits which is very close to the target but insufficient. When the imperfections of the real products are considered, the gathered luminance should exceed the target value. Figure 85 can be referred for the luminance distribution of the TV which is at acceptable level in terms of visual performance. The 9 points luminance uniformity results are represented in Table 14. The minimum uniformity point luminance is 77 % which is above the target luminance.

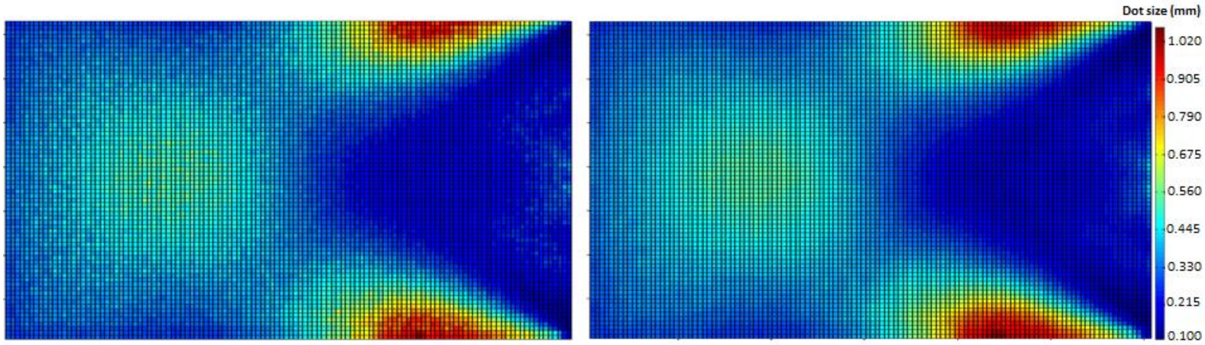


Figure 84: (a) Dot size distribution of LGP texture of XBD and LGT. (b) 3x3 low pass filtered LGP pattern

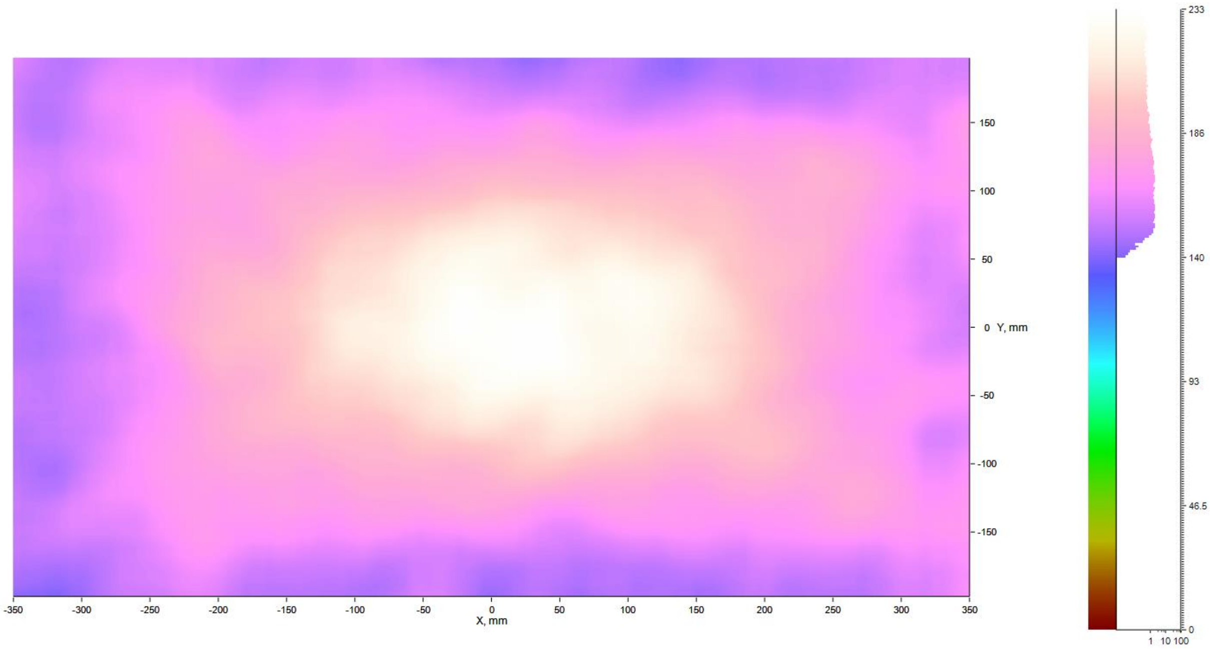


Figure 85: Luminance distribution result of the Cree XBD and LGT

Table 14: Luminance uniformity results of Cree XBD and LGT design

9 Points Luminance Uniformity Results			
	H/4	H/2	H/4
V/4	176	193	185
V/2	193	230	203
V/4	178	190	187

9 Points Luminance Uniformity Ratios			
	H/4	H/2	H/4
V/4	77%	84%	81%
V/2	84%	100%	88%
V/4	78%	83%	81%

3.4.2 Cree XBD Corner

Direction of the XBD LEDs is 60° rotated to the LGP's inner side for direct corner-lit design. The corner placement of the bottom LEDs can be seen in Figure 86. It is possible to ease the design by illuminating the TV from the four corners with new LEDs, however such an approach is disadvantageous in case of manufacturing and cost aspects, so it is decided to continue with two corner illumination structure. As shown in Figure 87the cross-sectional view of LED and LGP, LED-LGP coupling is at enough level to prevent the light leakages from top and bottom sides of the LGP with the help of small LED dimensions.

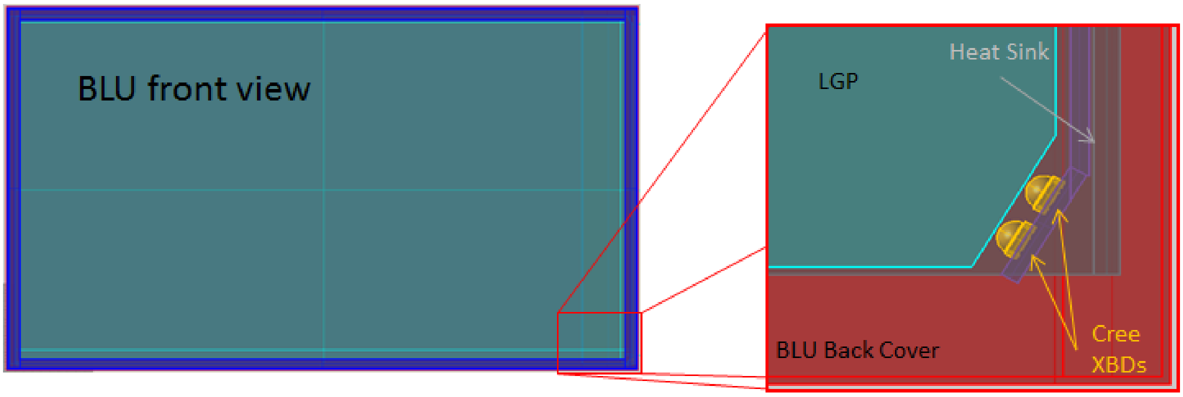


Figure 86: The placement of the Cree XBD in the display.

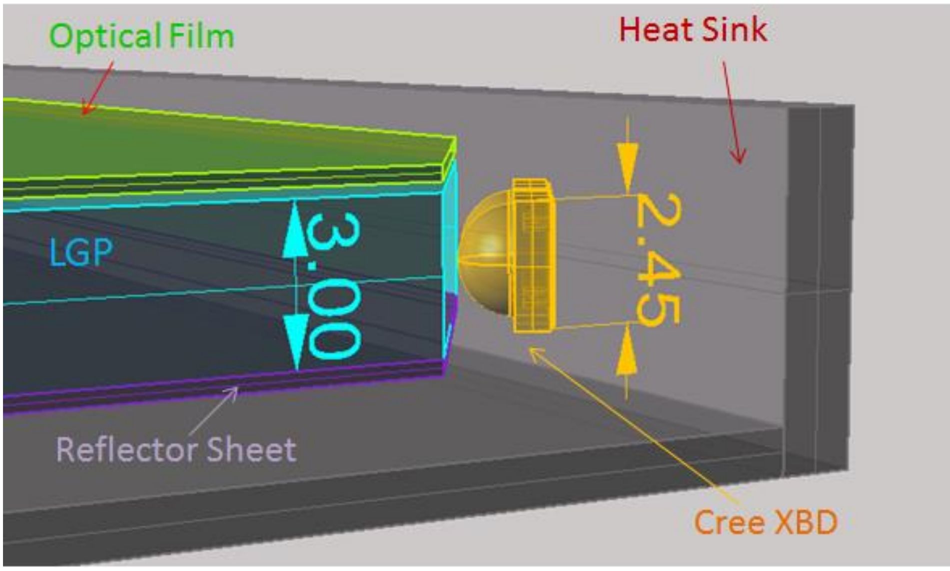


Figure 87: Cross-sectional view of Cree XBD and LGP placement

The result of the pattern studies of the LGP can be seen in Figure 88. As can be seen from the dot size distribution, the weak point of the light distribution is the short edge of the TV which is close to the LEDs. This situation is occurred because the LEDs are angularly more headed towards the far edge. This angular orientation provides that the light reaches the far edge without losing intensity. The left hand side of the figure shows the simulation result and the right hand side shows the low pass filtered of the pattern. Luminance distribution result which is obtained by the below given pattern distribution, is shown in Figure 89.

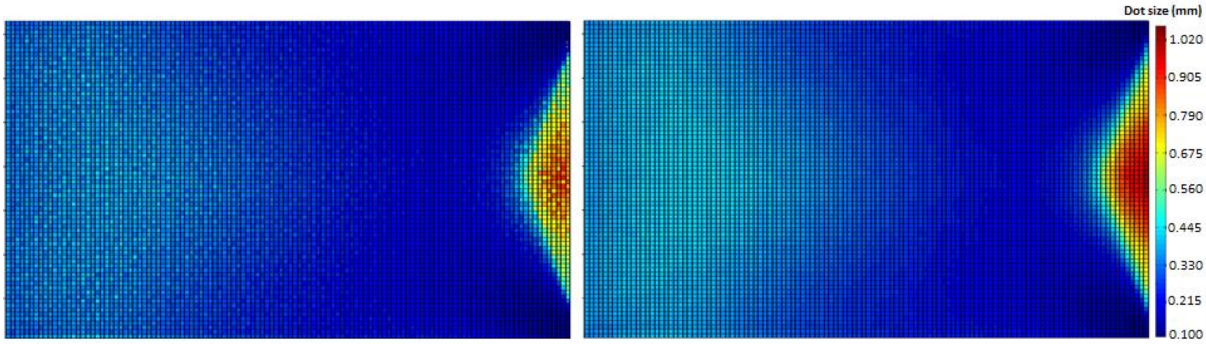


Figure 88: (a) Dot size distribution of LGP texture of XBD direct corner-lit. (b) 3 by 3 low pass filtered LGP pattern

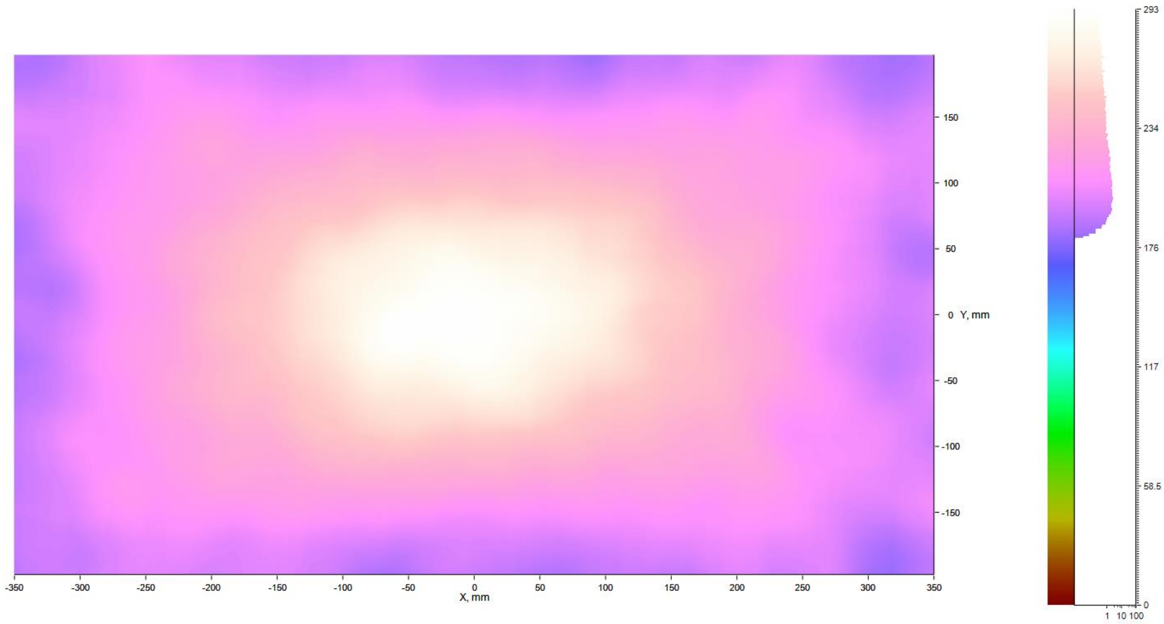


Figure 89: Luminance distribution result of the Cree XBD

It is seen from the TV's 9 points luminance uniformity results, which are given in Table 15 that the uniformity level is 77% and the center luminance is 291 nits. According to these results, both optical targets are achieved by using the optical structure which is explained in this section.

Table 15: Luminance uniformity results of Cree XBD direct corner-lit design

9 Points Luminance Uniformity Results			
	H/4	H/2	H/4
V/4	224	241	223
V/2	245	291	241
V/4	227	242	225

9 Points Luminance Uniformity Ratios			
	H/4	H/2	H/4
V/4	77%	83%	77%
V/2	84%	100%	83%
V/4	78%	83%	77%

3.4.3 Luxeon Corner

In order to understand the effects of LED shape differences to the optical performance of the system Philips Luxeon Z ES LEDs are examined. The LED placement in the BLU is shown in Figure 90. The LED LGP coupling is very effective as can be seen in Figure 91 which help to decrease the light loses. LEDs active surface can be placed closer to LGP, as can be seen in Figure 92, compared to Cree XBDs, with the help of its flat top surface. The silicon flat top surface of Luxeon Z ES is 0.03 mm on the other hand the silicon dome of XBDs which covers the chip and phosphor has 0.99 mm thickness. The top dome shape makes the active light emitting part farther away from the LGP coupling surface. The top surface shape difference provides to Luxeon less light leakage than XBD. Even whole package thickness of Luxeon Z ES is slimmer than XBD dome which is only 0.59 mm.

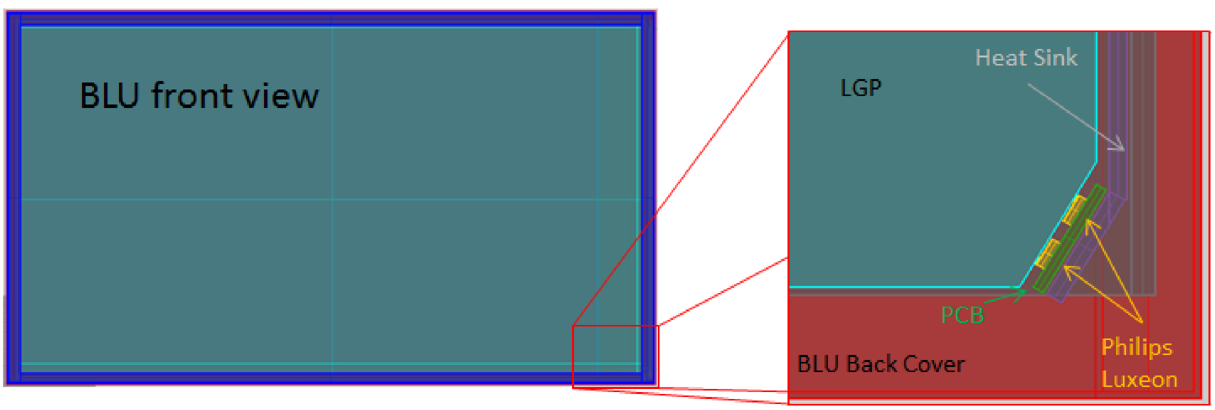


Figure 90: The placement of the Philips Luxeon Z ES in the display.

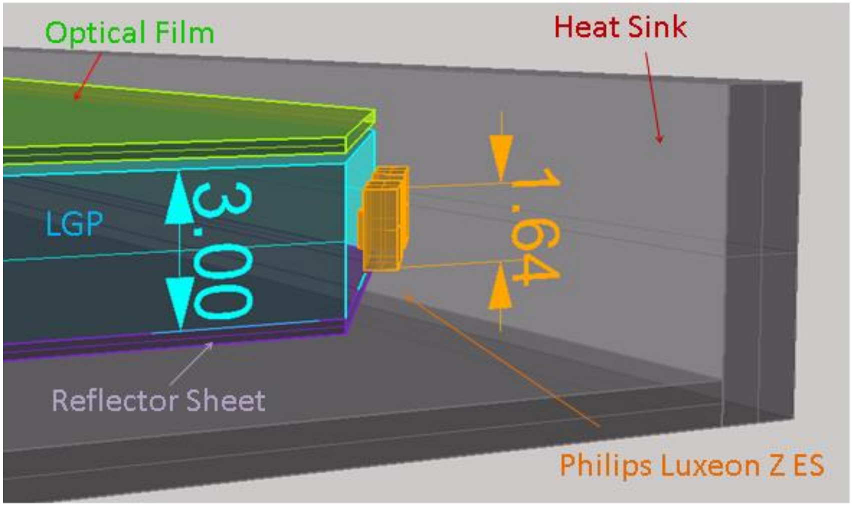


Figure 91: Cross-sectional view of Luxeon Z ES and LGP placement

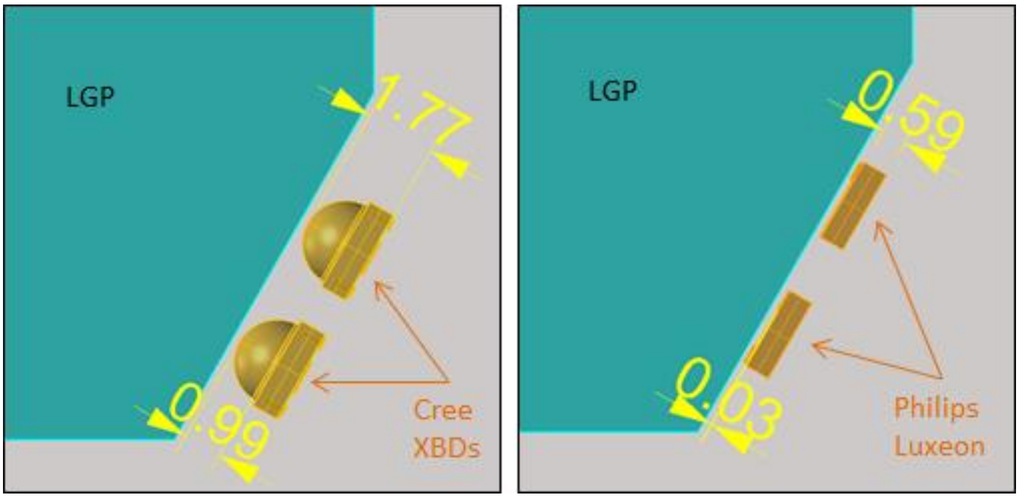


Figure 92: Dimensional comparison between Cree XBD and Luxeon Z ES in the direct corner-lit design structure

The LGP pattern result of Luxeon Z ES is shown in Figure 93. The distribution is almost same as XBDs as expected. The luminance distribution of the Luxeon can be seen in Figure 94 which is visually satisfying the TV targets without any luminance discontinuities.

According to the 9 points luminance uniformity results which are presented in Table 16, the center luminance is 316 nits and uniformity is 81%. Both results are highly satisfies the TV optical targets. These results show us that the best LED which can be used for corner-lit BLU, are the LEDs which has similar optical and dimensional features like Luxeon Z ES.

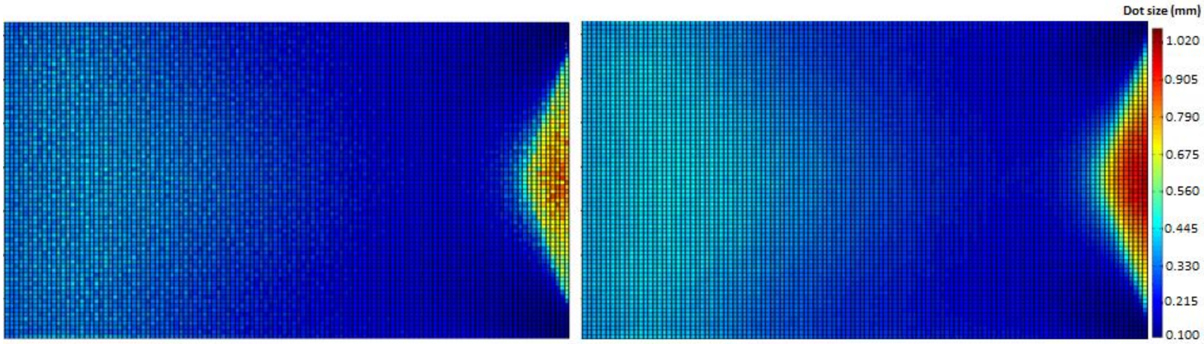


Figure 93: (a) Dot size distribution of LGP texture of LuxeonZ ES direct corner-lit. (b) 3x3 low pass filtered LGP pattern

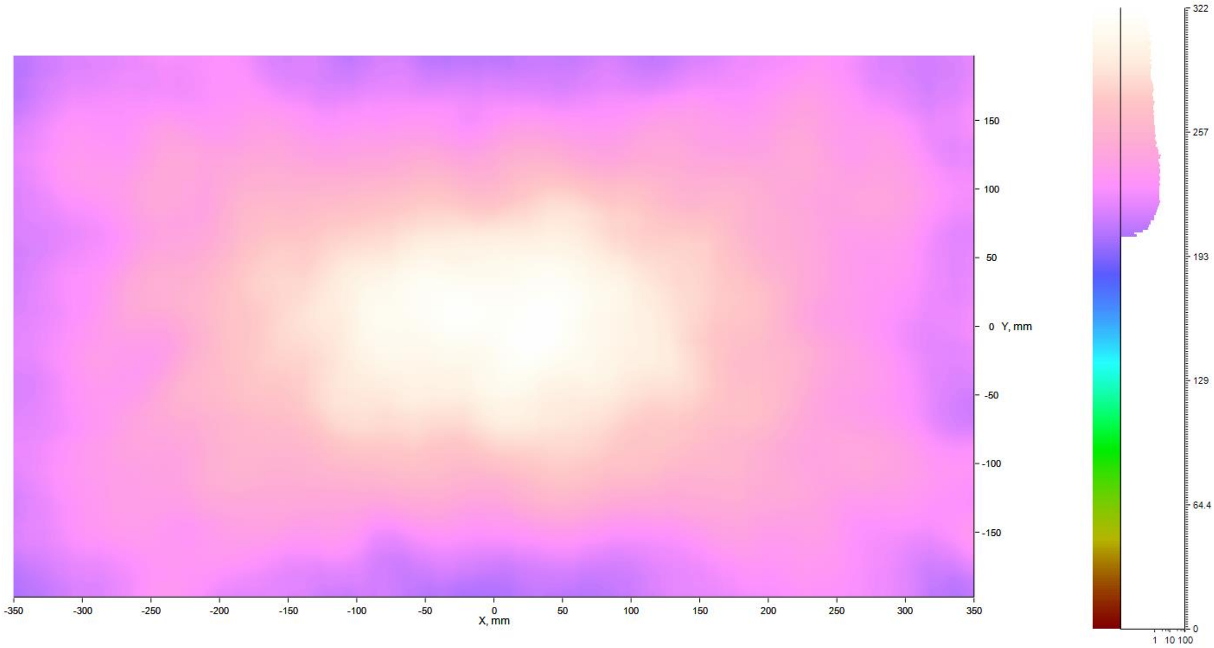


Figure 94: Luminance distribution result of the Philips Luxeon Z ES

Table 16: Luminance uniformity results of Luxeon Z ES direct corner-lit design

9 Points Luminance Uniformity Results			
	H/4	H/2	H/4
V/4	255	261	256
V/2	273	316	270
V/4	259	267	259

9 Points Luminance Uniformity Ratios			
	H/4	H/2	H/4
V/4	81%	83%	81%
V/2	87%	100%	86%
V/4	82%	85%	82%

In order to compare the luminance distribution and efficiency of the LEDs, XBD LEDs are evaluated with the LGP pattern of the Luxeon Z ES. The luminance distribution comparison can be seen in Figure 95. The areas marked as 1 and 2 have luminance discontinuities in XBD solution. This is not acceptable for a TV visual performance.

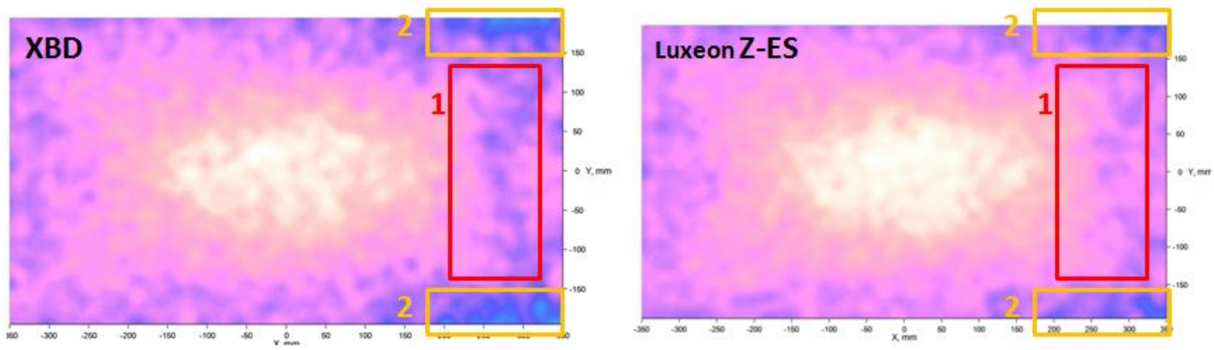


Figure 95: Luminance distribution comparison between XBD and Luxeon under same LGP pattern texture.

CHAPTER 4

OPTICAL MODELLING SUMMARY AND FUTURE RESEARCH

After achieving the optical design targets, the summary of the design studies and future research ideas are concluded in this chapter.

The optical simulation results of the critical optical parameters of each design approaches are presented in Table 17. The following conclusions from the optical design studies can be drawn as follows;

Table 17: Summary of the simulation results of various design architectures.

#	Name of the Design	Luminance (nits)	Luminance Comparison (%)	Uniformity (%)	Visual Performance
1	Cree XM-L2 Corner	N/A	N/A	N/A	NOT GOOD
2	Cree XM-L2 with LGT	198	63	77	OK
3	Cree XBD with LGT	230	73	77	OK
4	Cree XBD Corner	291	92	77	OK
5	Luxeon Z ES Corner	316	100	81	OK

- The emitting surface dimensions of the LEDs should be equal or smaller than LGP thickness for directional corner-lit BLU structure. For the current study, emitting surface dimensions should be smaller than 3 mm.
- Light guide tube (LGT) is an option for using the LEDs bigger than LGP dimensions. In order to increase the center luminance to achieve the target further study is needed.
- When the center luminance results of XBD with LGT and XBD corner designs are compared, it seems that LGT usage cause approximately 20 % optical efficiency losses to the system. The root cause of this loss is the medium changes between LGT, air and LGP.

When the real product is produced, this loss will be higher than 20 % due to LGT-LGP coupling will be worse because of mechanical imperfections of the system.

- In addition to design disadvantages of the LGT concept, due to the design includes more components (LGT and LED side reflectors) than direct corner-lit concept, the component cost of the system will be higher and the mass production process will be more complex.
- According to the XBD and Luxeon direct corner-lit design results, LEDs emitting surface shape has an important effect on the optical design. The dome shape decreases the center luminance approximately 8%. Furthermore, the 9 points luminance uniformity of dome shape is 4% lower than the flat type.
- New micro lens technologies have to be developed based on optical models and validated with the experimental findings
- Packaging those LEDs over the LED bar has to be investigated to avoid local packaging defects and obtain custom LED bars.
- When the flat type and dome type LEDs are evaluated with the same LGP pattern, dome type structure has luminance discontinuities (MURA) at the short edge of the display which is close to LEDs.

In order to increase the optical efficiency of the system, the optical film structure is defined as two prism sheets and one reflector polarizer. The required lumen output is decreased to 812 lm and the required power consumption is decreased to ~9 W levels with the help of this structure. The power consumption of designed structure is almost 60% lower than the conventional 32” LED TVs. The main purpose of this efficiency increment is to decrease the heat dissipation from the LEDs for efficient cooling and, to increase the possibility to find the LEDs with sufficient lumen output. However the optical film structure cost is very high for 32” size TV due to expensive reflective polarizer usage. Therefore, in order to get rid of reflective polarizer from the optical film structure the lumen output of the LEDs can be increased in future studies. To be able to increase the lumen output, number of LEDs can be increased or development of LEDs that can be driven at higher currents is necessary. In both cases the cooling system of the TV should be very efficient.

In addition to increment of lumen output and power consumption of the LEDs, light distribution can also be improved. According to the final LGP pattern dot size distribution shown in Figure 93, the short edge close to LEDs has almost 8 times higher dot sizes than center point. This shows that the angular light distributions of the LEDs are not well suited to corner design. The further study can be done to improve the angular light distribution of the LEDs. Chip on board (COB) flip chips which do not have packages, can be tried due to their wider beam angle. Another solution can be a secondary lens design on top of the lenses to change the lambertian distribution of the LEDs.

CHAPTER 5

THERMAL MODELLING

After finalizing the optical structure of the BLU, thermal design of the system should be defined to have a reliable product and to achieve safe junction temperature. According to the power consumption calculations indicated in formula 15, power consumption per LED is approximately 2W, which generates very high level of heat for a small LED package placed in enclosure. If the LEDs are not cooled down, because of their sensitivity to high temperature, the optical efficiency and life time specifications are highly dropped. In addition to LED junction sensitivity, other optical components like LGP and optical films can be deformed due to high temperature. Therefore, a very efficient cooling system should be designed for this structure.

$$PC = I_f * V_f * NoL \qquad (17)$$

$$PC_{L-zes} = 0.7 * 2.85 * 4 = 7.98\,W$$

Current 32" LED TVs in the market use standard aluminum heat sink for cooling. But the power consumption per LED is only 0.35W; therefore Al heat sink is sufficient for those kinds of designs. Due to small volume placement of the LEDs, it is not easy to dissipate the heat from the heat source. Therefore, rather than using a standard Al heat sink, advanced thermal materials should be investigated to reduce the thermal resistance of the design.

Graphite based or CVD like materials can be a solution for corner-lit BLU [17]. In this study, thermal pyrolytic graphite (TPG) is examined as a high conductive material.

TPG is decomposed under high temperature and high pressure environment with hydro carbon gases. Its molecular structure is ordered in three dimensions. Thermal conductivity of TPG is higher than 1500 W/mK in two dimensions with the help of its molecular structure. In the third dimension, thermal conductivity is only around 10 W/mK. In addition to thermal conductivity advantage the density of the TPG is only 2.2 g/cc which is lighter than aluminum. Thermal conductivity and density comparison of heat sink materials are presented in Table 18. According to these values, TPG is a good candidate to build a high efficient cooling system. [27]

Table 18: Thermal conductivity and density comparison of materials

Material	In-Plane TC (w/m-K)	In-Plane TC (w/m-K)	Specific Gravity g/cm³
Aluminum	218	218	2.7
Copper	400	400	8.9
Carbon	400	40	1.9
CVD Diamond	1100-1800	1100-1800	3.5
TPG Graphite	1500-1700	10	2.3

5.1 Thermal System Approach

Before starting the thermal modeling, the mechanical structure of the LED and heat sink is determined. Luxeon Z ES LEDs are mounted on a metal core PCB (MCPCB). The MCPCB is attached to the TPG by using a thermal tape. Due to high price of TPG, it is used as a first dissipater. In order to dissipate the heat to the metal back cover of the TV from a wide surface, an Al heat sink is defined. The cross-sectional view of the thermal system stack can be seen in Figure 96. The placement of the LEDs and other component placement details, which are determined according to optical modeling, can be seen in Figure 97.

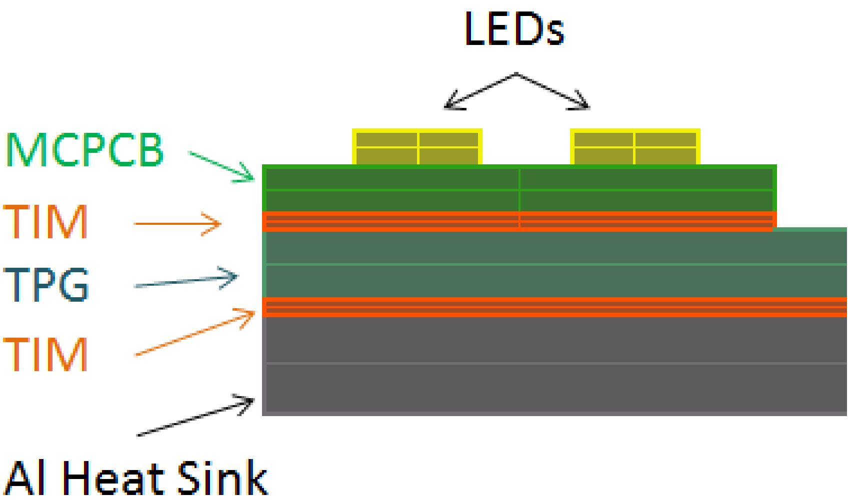


Figure 96: Thermal solution stack of the design

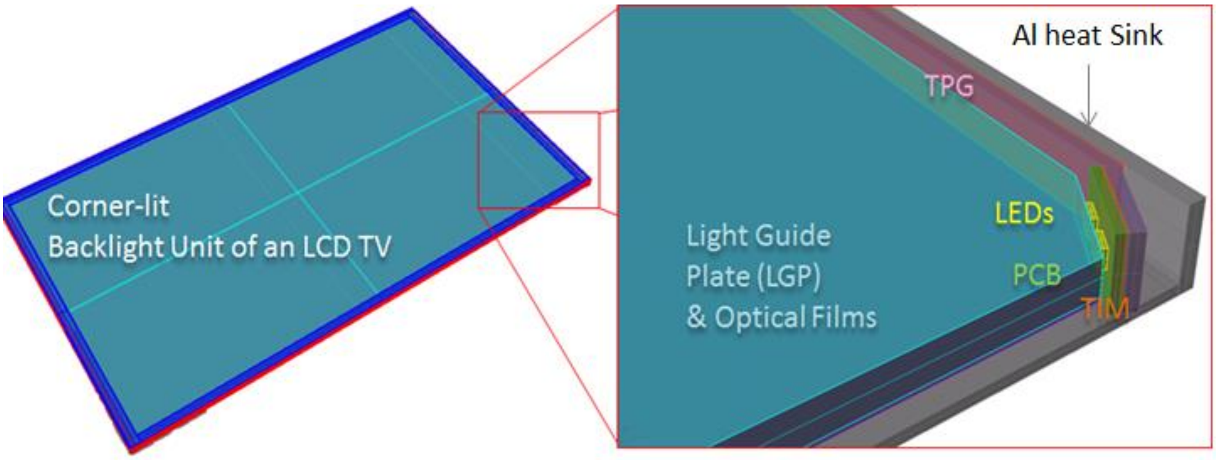


Figure 97: Mechanical structure for thermal design of corner-lit LED TV [25]

In the first step of the thermal studies, thermal resistance network diagram is created for the idealized corner-lit TV design according to the explained mechanical structure as can be seen in Figure 98. Mechanical dimensions, thermal conductivities and calculated thermal resistance of the components are shown in Table 19.

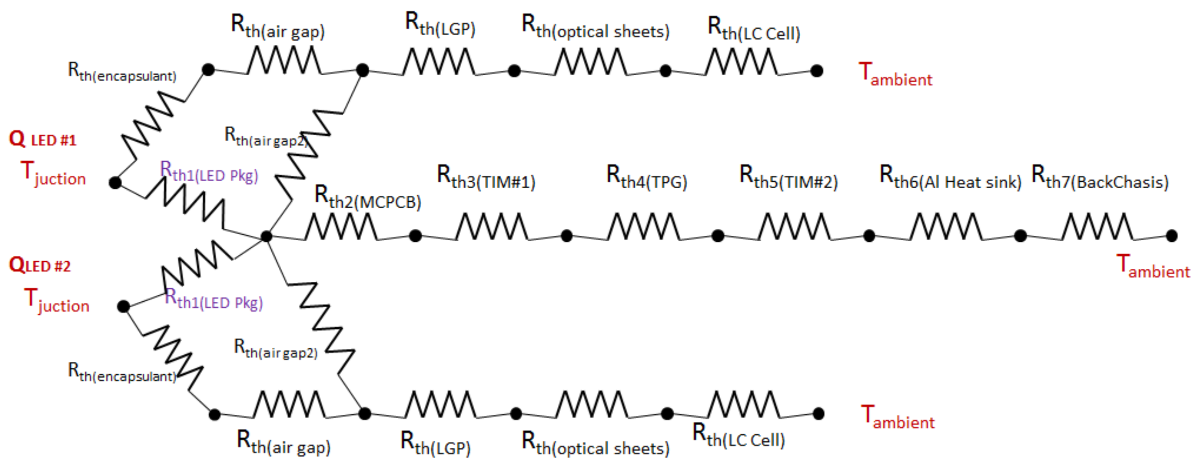


Figure 98: Idealized thermal resistance network of the corner-lit TV

Table 19: Thermal conductivities and the resistances of the design

Components		**K (W/mK)**	**T (m)**	**x (m)**	**y (m)**	**A (m²)**	**Rth (K/W)**
LED		-	-	-	-	-	3.000
MCPCB	**Cu**	400	5.00×10^{-5}	6.20×10^{-3}	8.24×10^{-3}	3.40×10^{-5}	0.004
	D/L	10	8.50×10^{-5}	6.20×10^{-3}	8.24×10^{-3}	5.11×10^{-5}	0.166
	AL	177	6.15×10^{-4}	6.20×10^{-3}	8.24×10^{-3}	5.11×10^{-5}	0.068
TIM #1		1.2	2.50×10^{-4}	6.20×10^{-3}	8.24×10^{-3}	5.11×10^{-5}	4.078
TPG		1350/1350/10	1.10×10^{-3}	6.20×10^{-3}	1.00×10^{-1}	6.20×10^{-4}	0.177
TIM #2		1.2	2.50×10^{-4}	6.20×10^{-3}	1.00×10^{-1}	6.20×10^{-4}	0.336
Al Heat Sink		177	1.60×10^{-3}	6.80×10^{-2}	2.00×10^{-1}	1.36×10^{-2}	0.001
BC		45	5.00×10^{-4}	5.74×10^{-2}	2.00×10^{-1}	1.15×10^{-2}	0.001

The system is carried the high heat from the LEDs along the TPG very efficiently and the heat is transferred to the Al heat sink to distribute the energy into a large area. The heat transfer along TPG is represented in Figure 99. In order to understand the efficiency of the design ANSYS ICEPAK (REF) computational fluid dynamics (CFD) program is used.

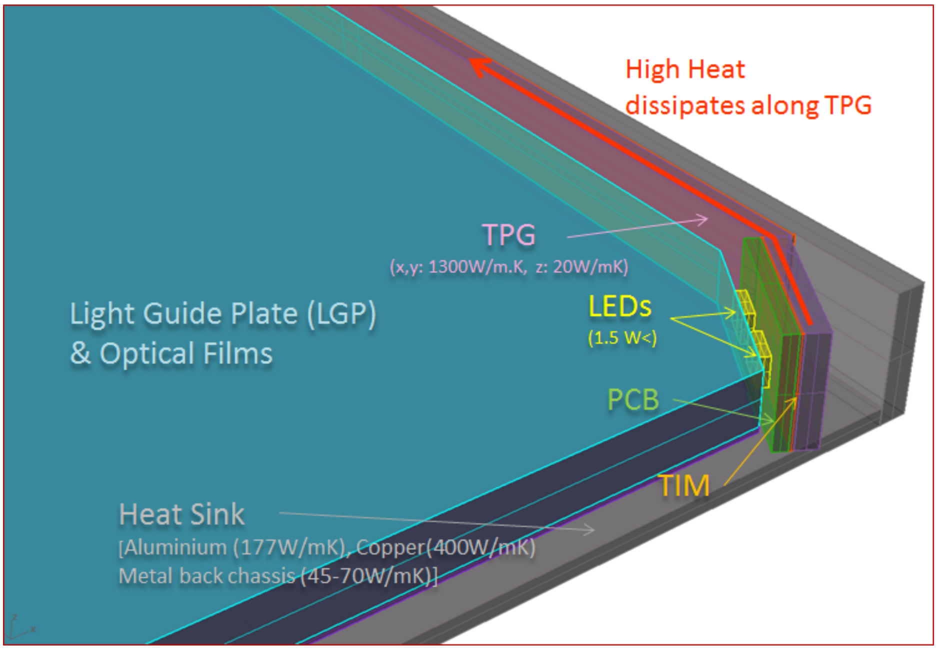


Figure 99: Heat dissipation along TPG sketch of the design

5.2 Computational Study

In order to run a simulation in ICEPAK, properties of the design should be defined in the program. In order to fasten the computational studies, no thermal interface resistances are accounted for and perfect bonding is assumed in the models. Some other critical parts of the system are explained in this section.

5.2.1 Material Properties

To be able to see the temperature distribution of the system heat generation of the LEDs and thermal conductivities of the materials in the system should be defined. In the first step, LEDs total heat power is defined according to the optical study results presented in the previous chapters. The total power of one Luxeon LED is almost 2 W. Approximately only 20% of this power can be converted to the visible light. The rest is turned into heat; therefore the heat powers of the Luxeon LEDs are set to 1.6 W in the program.

Thermal conductivity of metal back cover (BC) of the TV is defined according to the widely used material electro galvanized steel (SECC) as 45 W/m-K. Metal BC setting window of ICEPAK can be seen in Figure 100. Plastic based materials which are optical films (PET), LGP (PMMA) and middle frame (PC) are set as 0.2 W/m-K. The metal core PCB has three thin layers indicated in Table 19. In order not to have meshing problems in the program, MCPCB defined as one layer. The layer conductivity is calculated by using formula number 14 and 15. According to the calculations the conductivity is 61.67 W/m-K. TIMs placed between MCPCB-TPG and TPG-Al heat sink are defined according to the widely used thermal tapes in the market, which is 1.2 W/m-K. Thermal conductivity values of the materials for ICEPAK can be seen in Table 20.

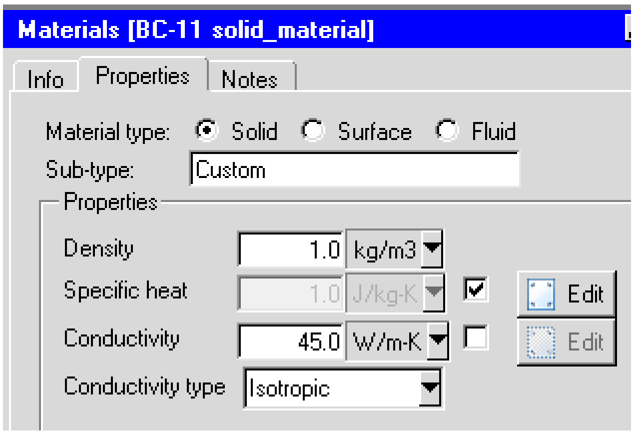


Figure 100: Metal BC property window in ICEPAK

$$R_{MCPCB} = R_{Cu} + R_{DL} + R_{Al} = 0.004 + 0.166 + 0.068 = 0.238\ K/W \tag{18}$$

$$K = \frac{t}{A \times R_{th}} = \frac{7.5 \times 10^{-4}}{5.11 \times 10^{-5} \times 0.238} = 61.67\ {}^{W}/_{mK} \tag{19}$$

Table 20: Thermal conductivity values of materials for ICEPAK

Material	Thermal Conductivity (W/m-K)
TV Metal Back Cover	45
Plastic Middle Frame	0.2
Optical Films & LGP	0.2
Al Heat Sink	177
TPG	1350/1350/10
TIM	1.2
MCPCB	62

5.2.2 Assemblies and Mesh Control

One of the most important parts of thermal simulation programs is meshing. Therefore mesh sensitivity study is performed. In CFD model, not to create unnecessary fine mesh which causes lots of computational power usage, assembly parts can be defined. The location of the heat sources and the heat sink close to heat sources can be separated from the main meshing settings. For corner LED TV structure, two corners which locate the LEDs must be fine mashed. Furthermore, these corners are not only the heat source locations but also material transition locations in a very small volume. LEDs, MCPCB, TIMs and TPG are located at very close locations. This kind of material transitions must be fine mashed. In addition to the heat source corners, the Al heat sink is also separated as assembly to be able to see the details of temperature gradients. The two corner LED-TPG and Al heat sink assembly partitions are shown with pink borders in Figure 101.

Mesh properties of the assembly parts are defined separately from the general mesh settings. For metal BC, plastic middle frame, optical films and LGP parts which are out of assembly parts included in general mesh settings which are shown in Figure 102. Mesh type is set to

Mesher-HD and the element sizes are defined as 8 mm, 8 mm and 2 mm for three dimensions. Minimum elements in gap section is set to 4. In order to have smooth element transitions Max Size Ratio is defined as 1.2. For the assembly parts of the design, max mesh element sizes in three dimensions are differentiated from general settings. The Al heat sink assembly max element sizes are 0.8 mm, 2 mm and 0.8 mm. Due to its dense transitions and it has heat sources, LED-TPG assemblies need more elements for better analysis. Therefore, the max element sizes are defined as 0.15 mm, 0.2 mm and 0.15 mm for three dimensions. The details of both Al heat sink and LED-TPG assemblies can be seen in Figure 103. As a result of these settings, number of elements is selected to be 5034002 and number of nodes is 5232701.

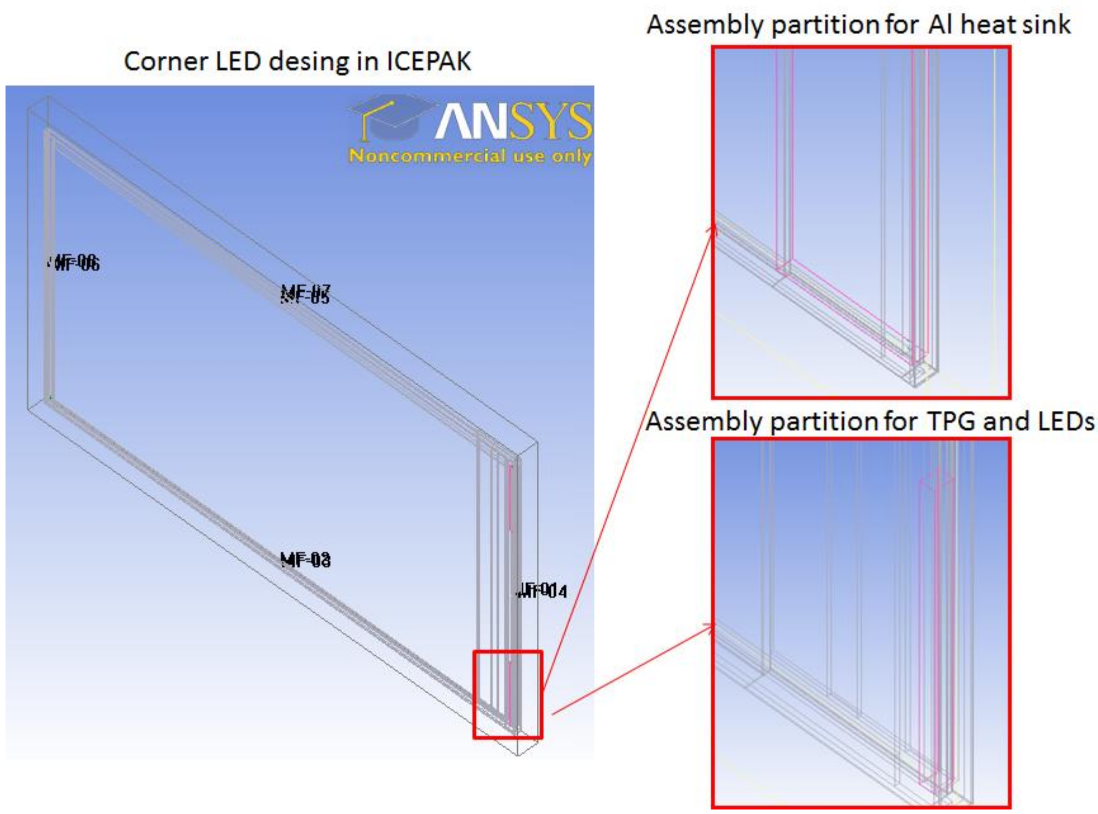


Figure 101: Assembly partitions of corner LED design

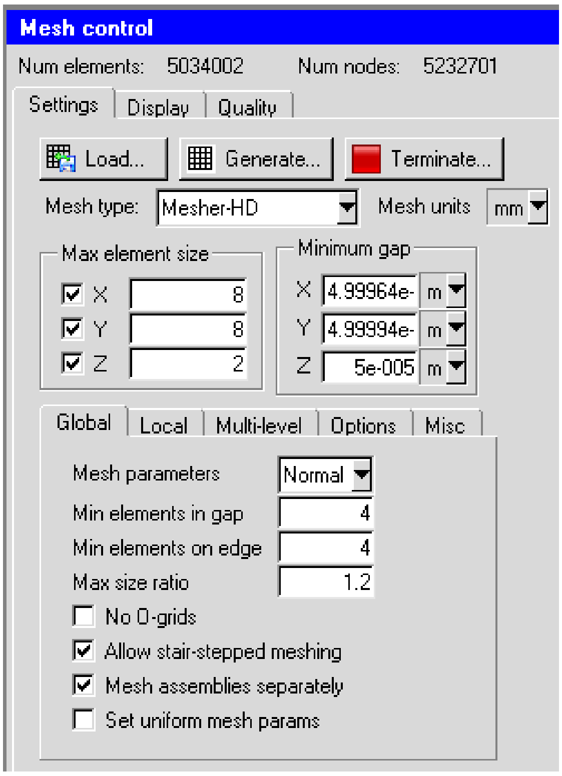


Figure 102: General mesh settings

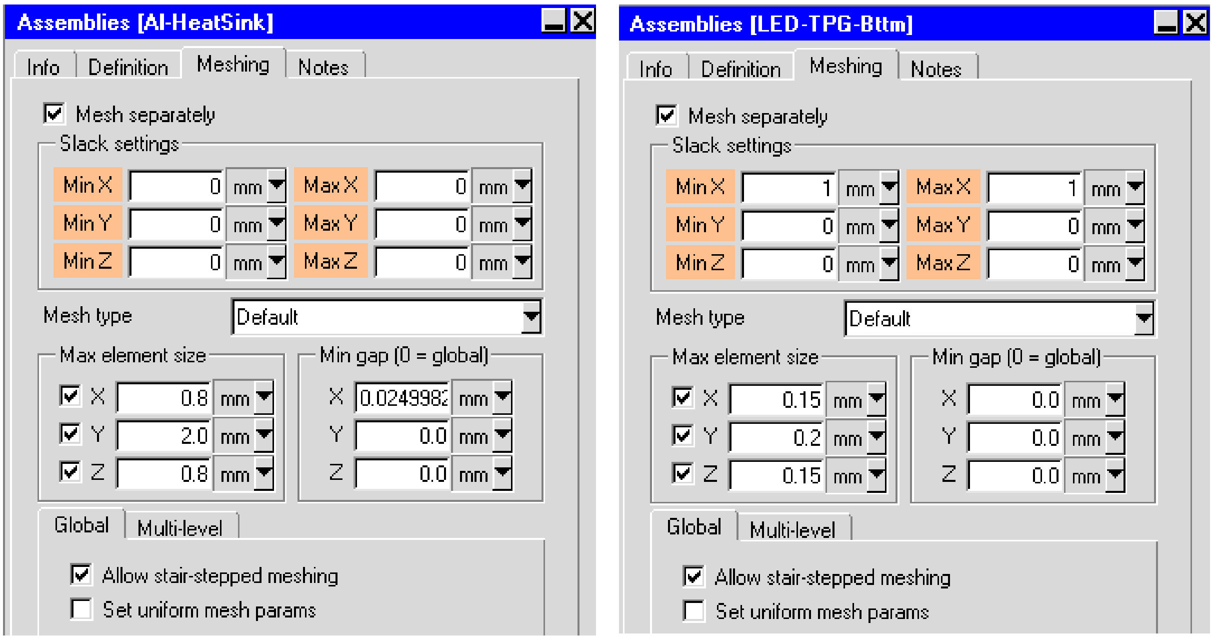


Figure 103: Assembly mesh settings

5.3 Application of Corner-Lit TV in the Thermal Models

After finalizing the parameter settings of ICEPAK, the simulation can be run. In the first step, insufficiency of conventional Al heat sink w/o TPG is simulated. After that, thermal results of different TPG thicknesses and TPG lengths are examined. Then the most efficient dimensions are defined as a solution.

5.3.1 MCPCB and Al Heat Sink

Al heat sink is the conventional cooling system for LED TVs. Al heat sinks are sufficient passive cooling systems for mid power LEDs in TV systems. In the first simulation, the insufficiency of Al heat sink for corner-lit TV is shown. The front view of the LEDs located at the top side of the TV is shown in Figure 104. . Other than LED, MCPCB, TIM and Al heat sink components are turned to invisible for better analysis. Simulation is performed for 600 iterations.

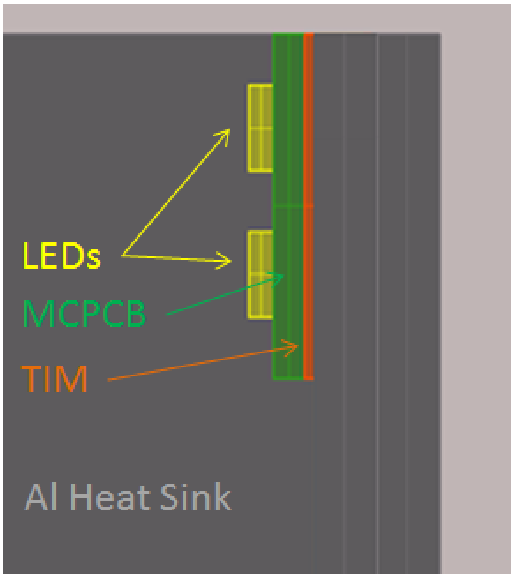


Figure 104 Front view of the LEDs located at the top side of the TV for MCPCB-Al Heat Sink solution

The LED junction temperature result is 100.5 °C which is much higher than target LED junction temperature which is defined as 85 °C in the first chapter. The temperature distribution of the LEDs and the heat sink can be seen in Figure 105. 100.5 °C junction temperature leads us to a junction to ambient resistance of 47.2 K/W by using formula number 16. The computational result proves that Al heat sink usage is not enough to cool down high power LEDs in TV systems.

$$R_{th} = \frac{(T_j - T_{amb})}{Q} = \frac{(100.5 - 25)}{1.6} = 47.2\ K/W$$

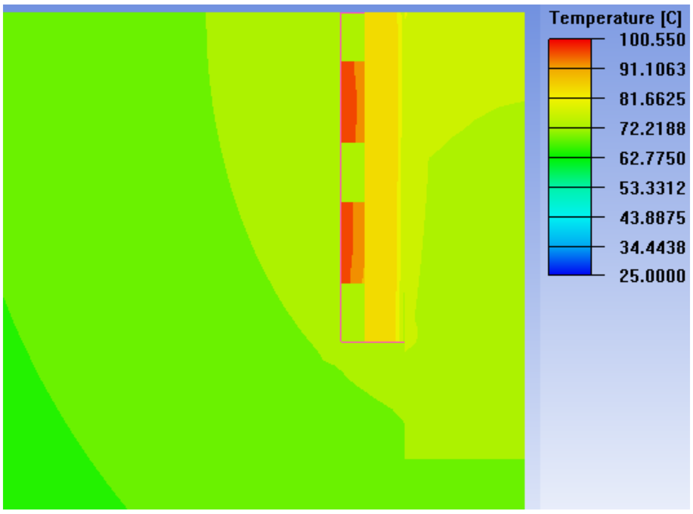


Figure 105: Temperature distribution of top side LEDs with Al heat sink

5.3.2 MCPCB, TPG and Al Heat Sink

Front view of the LEDs located at the top side of the TV can be seen in Figure 106. LEDs, MCPCB, TIMs, TPG and Al heat sink are visible in this view. Other components are turned to invisible for better analysis. TPG thickness is defined as 0.5 mm and TPG length is defined as 8.2 mm which is same as MCPCB length for the first simulation.

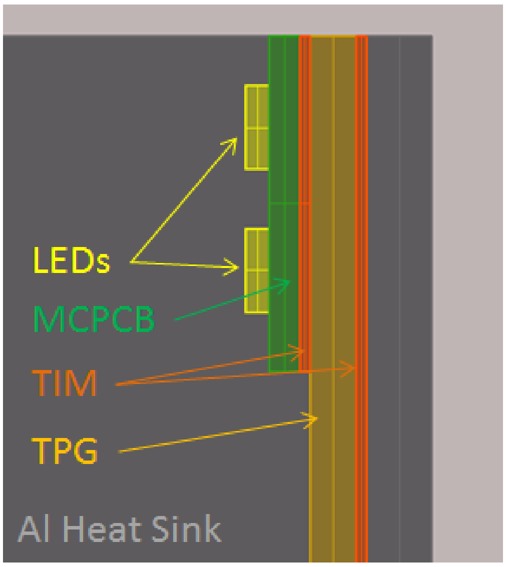


Figure 106: Front view of the LEDs located at the top side of the TV for MCPCB-TPG solution

Simulation is performed for 600 iterations. Temperature distribution of the panel and top side LEDs are shown in Figure 107. According to the temperature results, the maximum temperature in LED package is 89.6 °C. This level is higher than target LED junction temperature 85 °C. In order to understand the TPG dimension effects on the thermal system and to achieve the target LED junction temperature, more simulations are run with the following dimensions of TPG. Length of TPG is started from MCPCB length 8.2mm. Then 50 mm, 100 mm and 200 mm length TPGs are simulated. The thickness of TPG is defined as 0.5 mm, 1.1 mm and 2 mm for all TPG lengths. The LED junction temperature results of these trials are shown in Table 21.

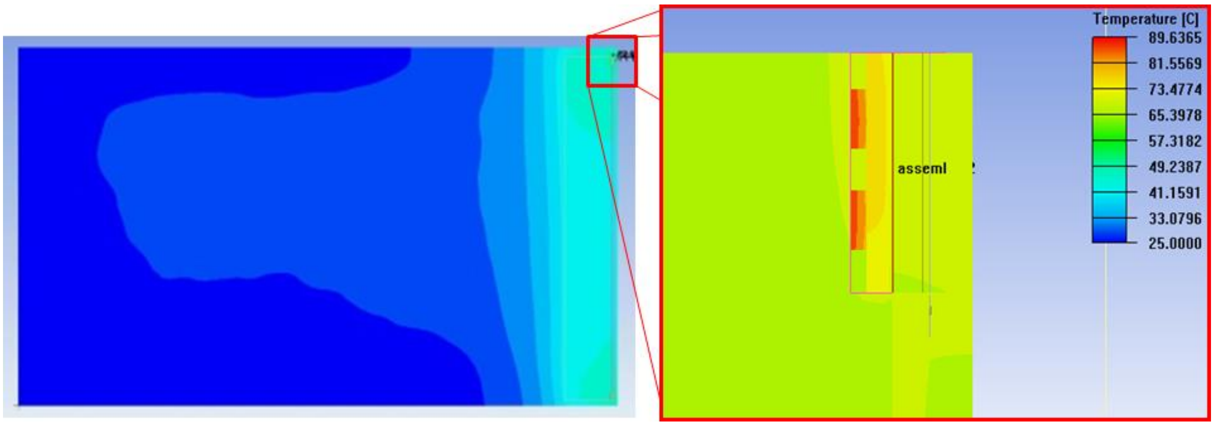


Figure 107: Temperature distribution of TV and top side LEDs with MCPCB and TPG (8.2mm.x 0.5mm)

According to the simulation results, if the thickness and length of the TPG is increased, the junction temperature is decreased as expected. The graph of the LED junction temperature results seen in Figure 108 shows that 50 mm of TPG length makes the thermal system safe for each thickness. When the high price of TPG is taken into consideration, the best dimension is 0.5 mm x 50 mm. On the other hand, the TPG is not strength mechanically therefore; other TPG thicknesses should also be taken into consideration. As a result, TPG usage can decrease the junction temperature to TV target. 80.2 °C junction temperature leads us to a junction to ambient resistance of 32.5 K/W.

Table 21: LED junction temperature results for different TPG length and thickness

TPG Length (mm)	**8.2**	**50**	**100**	**200**
TPG Thickness 0.5 mm	89.6	80.2	78.5	77.6
TPG Thickness 1.1 mm	84.9	78.6	76.3	75.5
TPG Thickness 2.0 mm	83.5	75.4	73.0	72.3

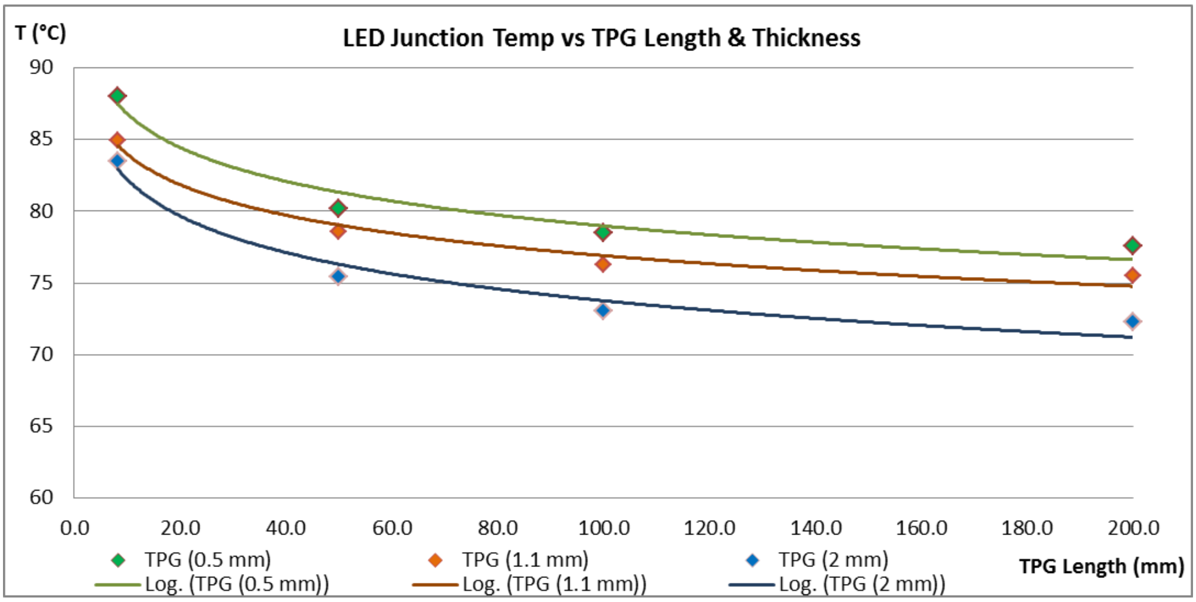


Figure 108: LED junction temperature vs TPG length and thickness

5.3.3 TPG and Aluminum Heat Sink

Using higher power LEDs to design more cost efficient TV backlight optical structure is proposed in previous chapter. When this proposal is taken into consideration in thermal management point of view, more efficient way can be proposed to cool down the LEDs by using TPG material. According to thermal resistance values represented in Table 19, the biggest resistance in the system is the TIM between MCPCB and TPG. In order to eliminate this part and to be able to use TPG high thermal conductivity directly, LED circuit can be printed on TPG. The front view of the LEDs and cooling system can be seen in Figure 109.

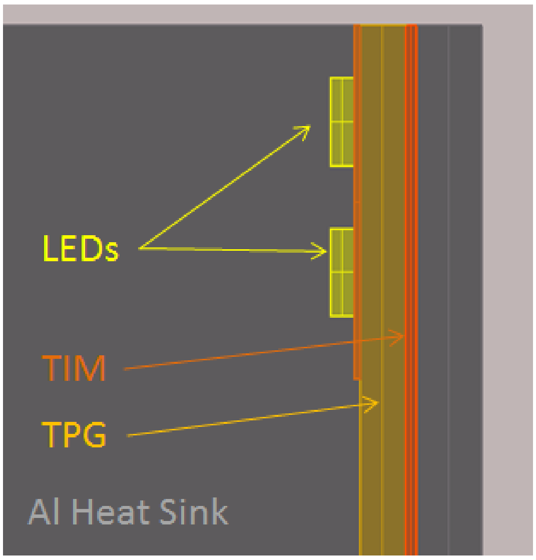


Figure 109: Front view of the LEDs located at the top side of the TV for TPG solution

Temperature distribution of the TV from the front view and detailed LED and cooling system are shown in Figure 110. LED junction temperature is decreased to 53 °C. In addition to lower junction temperature, the temperature distribution is more uniform in both TV and heat sink side than MCPCB solution. The thermal resistance between ambient and junction is calculated as 17.5 K/W.

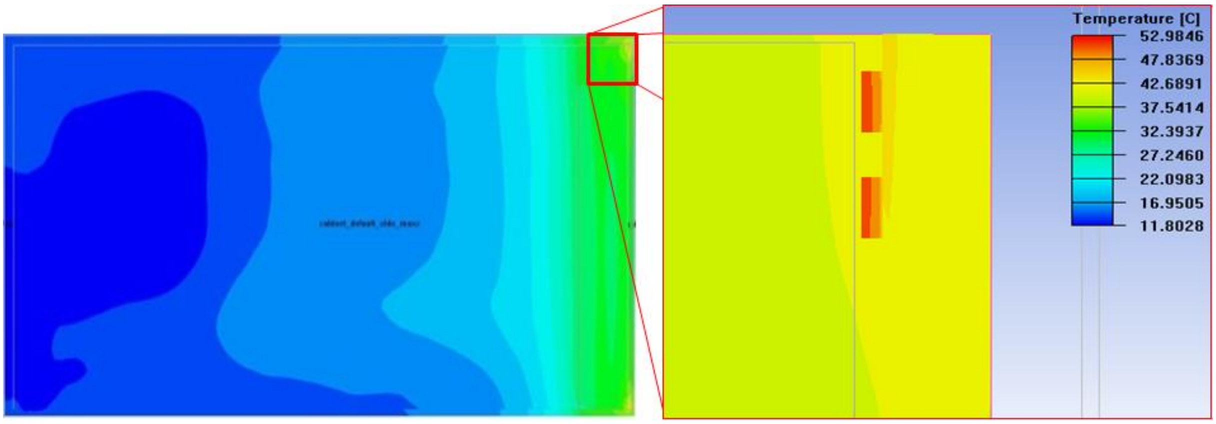


Figure 110: Temperature distribution of TV and top side LEDs with TPG (200mm.x 1.1mm)

Junction temperature results of other TPG dimensions and their comparison with MCPCB-TPG are presented in Table 22 and in Figure 111.

Table 22: LED junction temperature results of LEDs on TPG and LEDs on MCPCB with different lengths

TPG Length (mm)	**8.2**	**50**	**100**	**200**
LED on PCB & TPG	84.9	78.6	76.3	75.5
LED on TPG	60.7	57.8	55.4	53.0

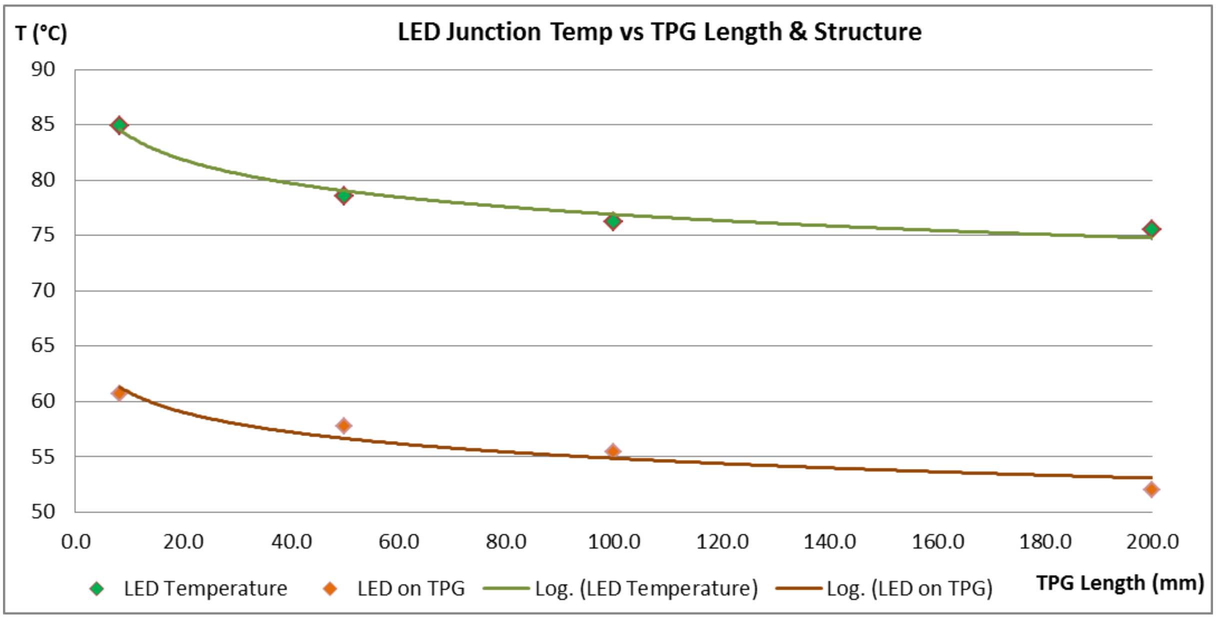


Figure 111: LED junction temperature graph of LEDs on TPG and LEDs on MCPCB with different lengths

These results shows that circuit printing on to TPG can be a good solution for very high power corner LED systems.

CHAPTER 6

THERMAL MODELLING SUMMARY AND FUTURE RESEARCH

The computational results, evaluation of thermal design studies and future research ideas are concluded in this chapter.

- According to computational results, the conventional LED TV cooling system Al heat sink is not sufficient for high power corner-lit BLU design. The LED junction temperature is resulted 100.5 °C. The insufficiency of the conventional system is observed even with the most efficient optical structure.
- If the TPG used in the thermal system, the high heat can be removed from the LED region of the TV. With the help of TPG usage, the LED junction temperature is decreased approximately 30% compared to conventional thermal design.
- The temperature difference is changed according to mechanical dimensions of TPG. The LED junction temperature differentiations of different TPG geometries compared to Al heat sink are shown in Table 23. According to computational studies the TPG length is highly affected up to 50 mm for this heat power conditions.
- When the TPG price is taken into consideration, TPG usage poses significant cost issues. However, if the LED power needs to be increased due to optical efficiency drop, the TPG dimensions can be chosen accordingly.
- Development a technology for advanced heat spreader based LED bar will be vital for corner LED systems.

Table 23: Junction temp. differentiation of TPG geometries compared to Al heat sink

TPG Length (mm)	**8.2**	**50**	**100**	**200**
TPG Thickness 0.5 mm	86%	73%	71%	70%
TPG Thickness 1.1 mm	79%	71%	68%	67%
TPG Thickness 2.0 mm	77%	67%	64%	63%

When the printed circuit is applied directly on to TPG in order to eliminate the thermal resistance of MCPCB and TIM, the junction temperature is decreased more than 50% compared to Al heat sink solution. The LED junction temperature difference of various TPG geometries compared to Al heat sink can be seen in The TPG junction cooling performance is increased approximately 40% when the circuit printing applied on TPG rather than MCPCB. The thermal resistance of LED junction to ambient is decreased from 32.5 K/W to 17.5 K/W. This result shows that higher power LED usage is possible with TPG heat sink and the possibility of corner-lit BLU.

Table 24 The TPG junction cooling performance is increased approximately 40% when the circuit printing applied on TPG rather than MCPCB. The thermal resistance of LED junction to ambient is decreased from 32.5 K/W to 17.5 K/W. This result shows that higher power LED usage is possible with TPG heat sink and the possibility of corner-lit BLU.

Table 24: Junction temp. differentiation of TPG geometries compared to Al heat sink

TPG Length (mm)	**8.2**	**50**	**100**	**200**
LED on TPG	47%	43%	40%	37%

One of the critical future study topics which need to be investigated is the bending of the TPG for angular LED positioning for optical design. The bending process should be performed with a special method, in order not to disrupt much the order of the structured molecules. If the structure order is disrupted, the high thermal conductivity property of TPG will be decreased. In addition, the low mechanical strength of TPG is also an obstacle for bending. To be able to safely bend the TPG the mechanical dimensions and a high conductive cover for increase the strength can be checked.

REFERENCES

[1] Paul Semenza, 2014, The Display Industry Shifts to Mobile. In: Display Search, *SID Display Week 2014*, San Diego, USA, 2-6 June 2014.

[2] Wikipedia, 2009, *LCD RGB sub pixel*. [online] Available at: <http://pl.wikipedia.org/wiki/Plik:LCD_RGB_subpixel.jpg> [Accessed 11 December 2014]

[3] Display Search, *Q3'12 Quarterly LED & CCFL Backlight Cost Report*, 2012, Display Search AN NPD Group Company, October 2012.

[4] FROGS Astronomy, *Overview of Stellar Spectra*. [online] Available at:. <http://quarknet.fnal.gov/fnal-uc/quarknet-summer-research/QNET2010/Astronomy/> [Accessed 11 December 2014]

[5] HyperPhysics, 2014,*Light and Vison*. [online] Available at: <http://hyperphysics.phy-astr.gsu.edu/hbase/hframe.html> [Accessed 12 December 2014]

[6] Wikipedia, 2014, *Luminance*. [online] Available at: <http://en.wikipedia.org/wiki/Luminance> [Accessed 12 December 2014]

[7] Wikipedia, 2014, *Luminous Flux*. [online] Available at: <http://en.wikipedia.org/wiki/Luminous_flux> [Accessed 12 December 2014]

[8] Wikipedia, 2010, *Eye sensitivity*. [online] Available at: <http://en.wikipedia.org/wiki/File:Eyesensitivity.png> [Accessed 12 December 2014]

[9] Cree, 2014, *LED Components & Modules*. [online] Available at: <http://www.cree.com/LED-Components-and-Modules/Products/XLamp/Discrete-Directional/XLamp-MLB> [Accessed 12 December 2014]

[10] ECSE, *White light sources based on wavelength converters*. [online] Available at: <http://www.ecse.rpi.edu/~schubert/Light-Emitting-Diodes-dot-org/chap21/chap21.htm> [Accessed 12 December 2014]

[11] Xbitlabs, 2003, *Monitors*. [online] Available at: <http://www.xbitlabs.com/articles/monitors/display/response.html> [Accessed 16 January 2015]

[12] Wikipedia, 2014, *NTSC*. [online] Available at: <http://en.wikipedia.org/wiki/NTSC> [Accessed 14 December 2014]

[13] International Committee for Display Metrology (ICDM), 2012. *Information Display Measurements Standard Version 1.03*, pp.28, June 1, 2012

[14] Masaru Suzuki, 2014. Optical Coatings and Films for LCD Backlighting, Seminar Lecture Notes, Society for Information Display, ISSN 0887-915X.

[15] 3M Optical Systems Division Liquid Crystal Display Customer Quality Specification Vikuit Dual Brightness Enhancement Film Diffuse - DBEF-D2-400

[16] 3M, *Optical Systems Optics 101*. [online] Available at: <http://solutions.3m.com/wps/portal/3M/en_US/NA_Optical/Systems/BehindTheScenes/Optics101/> [Accessed 15 December 2014]

[17] M. Arik, K. Karsli, *Effect of Optical Design on the Thermal Management for the Smart TV LED Backlight Systems*, IEEE 64th Electronic Components and Technology Conference, Florida, 2014

[18] International Committee for Display Metrology (ICDM), 2012. *Information Display Measurements Standard Version 1.03*, pp.21, June 1, 2012

[19] TOPCON Technohouse Corporation, *Products*. [online] Available at: <http://www.topcon-techno.co.jp/en/products/op_meas/sr-ledw.html> [Accessed 14 December 2014]

[20] Wikipedia, 2013, *CIE 1931 Color Space*. [online] Available at: <http://en.wikipedia.org/wiki/CIE_1931_color_space [Accessed 12 December 2014]

[21] Cree, 2014, *LED Components & Modules*. [online] Available at: <http://www.cree.com/led-components-and-modules/products/xlamp/discrete-directional/xlamp-xml> [Accessed 12 December 2014]

[22] Cree, 2014, *LED Components & Modules*. [online] Available at: <http://www.cree.com/led-components-and-modules/products/xlamp/discrete-directional/xlamp-xpg2> [Accessed 12 December 2014]

[23] Cree, 2014, *LED Components & Modules*. [online] Available at: < http://www.cree.com/led-components-and-modules/products/xlamp/discrete-directional/xlamp-xte-white> [Accessed 12 December 2014]

[24] Cree, 2014, *LED Components & Modules*. [online] Available at: <http://www.cree.com/led-components-and-modules/products/xlamp/discrete-directional/xlamp-xml2> [Accessed 12 December 2014]

[25] Cree, 2014, *LED Components & Modules*. [online] Available at: <http://www.cree.com/LED-Components-and-Modules/Products/XLamp/Discrete-Directional/XLamp-XBD> [Accessed 12 December 2014]

[26] Philips Lumileds, *Products Luxeon Z ES*. [online] Available at: <http://www.philipslumileds.com/products/luxeon-z-es> [Accessed 12 December 2014]

[27] K. A. Burke, I. Jakupca, A. Colozza, *Development of Passive Fuel Cell Thermal Management Technology*, 7th International Energy Conversion Engineering Conference (AIAA 2009-4656), Colarado, 2009

VITA

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